

ABSTRACT

Second-order, time-dependent, nonlinear, incompressible, shallow flow calculations have been developed to calculate models of tsunami waves propagating with continental slopes and shelves. Wave heights were observed to grow by a factor of 4 as they shoaled up a 1/16 continental slope. The effects of third wave action contributed to the largest wave run-up. Comparisons with shallow water, long wave calculations showed similar results, except for short wavelength tsunamis. The damping action of submerged barriers on tsunami waves was investigated. Significant portions of the energy of a tsunami may be reflected by submerged barriers. The numerical simulation of tsunami waves was performed at the Hawaii Institute of Geophysics, University of Hawaii, Honolulu, Hawaii.

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ABSTRACT

Two-dimensional, time-dependent, nonlinear, incompressible, viscous flow calculations were performed of realistic models of tsunami waves interacting with continental slopes and shelves. Wave heights were observed to grow by a factor of 4 as they shoaled up a 1/15 continental slope. The second or third wave often exhibited the largest wave run-up. Comparisons with shallow water, long wave calculations showed similar results except for short wavelength tsunamis. The damping action of submerged barriers on tsunami waves was investigated. Significant amounts of the energy of a tsunami may be reflected by submerged barriers. The numerical simulation of tsunami waves can provide realistic descriptions of their flow.

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I. INTRODUCTION

The objectives of this study were to determine whether time-dependent, nonlinear, viscous flow calculations of an incompressible fluid could be performed for gravity waves with extreme height to width ratios (approximately 1/100,000) of tsunami waves and to determine if the growth of the waves could be followed as they interact with the continental slope.

The SMAC (Simplified Marker and Cell) method of Amsden and Harlow (1) was chosen, and additional features were added to the ZUNI code including surface particles as described by Nichols and Hirt (2) and a partial cell boundary condition permitting boundaries to be placed across cell diagonals. The revised code is described in reference (3).

The ZUNI code has been adapted for use with the University of Hawaii IBM 360 model 65 computer and calculations were performed of waves that resemble tsunami waves. Street, Chan, and Fromm (4) used the MAC technique to numerically simulate long water waves and found that they could numerically reproduce the observed propagation of solitary waves in a horizontal channel and the run-up of a solitary wave on a vertical wall. Street, Chan, and Fromm's work did not consider waves of the height to width ratios of tsunami waves. Similar calculations were performed using the ZUNI code, and the vertical wall run-up results agreed with the experimental and numerical results of Street, Chan, and Fromm.

Recent calculations reported by Garcia (5) used the arbitrary boundary marker and cell technique to study tsunamis in the vicinity of their source. The method was applied to the Mendocino Escarpment for hypothetical ocean floor motions that might result from a major earthquake on the San Andreas Fault. The wave was followed numerically for the first 200 seconds. A single hump was first generated which split into two crests moving in opposite directions at a speed slightly less than shallow water wave speed. The waves were slightly dispersive, had a crest elevation above mean water level of about 1 m and a period

of about 1.5 minutes. The periods of major tsunamis measured in the Pacific Ocean are generally from 10 to 30 minutes. The periods are estimated from tide gage records assuming that the period remains nearly constant during the shoaling of the wave from the deep ocean. The wave height of major tsunamis is generally given as 1 ± 0.5 m and is estimated from the tide gage records assuming various approximate models for the wave height growth and extrapolating back to the deep ocean.

Present evidence suggests that tsunami waves consist of a train of several large, approximately sinusoidal waves of about 1 m in height, moving in the deep ocean at approximately the shallow water speed of \sqrt{gD} or 210 m/sec at the average Pacific Ocean depth of 4500 m, having periods of 10 to 30 minutes, wavelengths of 200,000 to 600,000 m and numerous smaller waves. It is the first 4 or 5 large waves that are of primary interest.

The numerical simulation of waves that have profiles similar to those suggested by experimental evidence, and the realistic simulation of the interaction of tsunami waves with the continental slope were the initial objectives of this study.

II. THE NUMERICAL MODEL

The details of the numerical method for solving the Navier-Stokes equations for viscous, incompressible flow, called SMAC, are described in references (1) and (3). The computing program, ZUNI, includes the free surface particles, a partial cell treatment that allows an obstacle face to pass through cell diagonals, and features that permit wave run-up on exposed sloping beaches in addition to submerged beaches.

Most of the calculations were performed with 15 cells in the Y direction and 68 cells in the X direction. The cells were rectangles 450 m high (ΔY) in Y direction and 6750 m long (ΔX) in X direction. The cell aspect ratio was 1/15. The time increment used was 3 sec. The convergence error used was 0.02. The water level was placed at 4550 m or 50 m up into the eleventh cell. The gravity constant was -9.8 m/sec². The viscosity coefficient used was 2.0 gm/sec-m (0.02 poise). This value is representative of the actual viscosity for water. Values

between 200 and 2.0 were tried and the viscosity did not significantly affect the results. This is as expected since the actual energy dissipation due to viscosity is only 1 in 10^7 for a viscosity of 200.

The stability requirements for the SMAC type of calculation are discussed in reference (2). Since the wave front must not pass through more than one cell in one time step, we have the stability criterion

$$C\Delta t < 2(\Delta X)(\Delta Y)/(\Delta X + \Delta Y)$$

where C is wave speed, ΔX and ΔY are cell widths, and Δt is the time increment. For the tsunami calculation described previously, the Δt must be less than 4 sec. We ran with 3 sec and had no evidence of instability; however, attempts to run with a time step of 9 sec always resulted in unstable numerical results which quickly turned to nonsense. While both Walsh and Harlow and Street, Chan, and Fromm(4) report that the MAC numerical method was observed to be stable for zero viscosity, analysis by Nichols and Hirt (2) suggests the perturbations could grow if the viscosity was not larger than about 20 and smaller than 30,000. We could not determine any difference between a viscosity of 200 and 2.0 for the tsunami calculation; so if perturbations are growing, it must be at a rate smaller than the errors associated with the iteration convergence criterion.

The original ZUNI code was written for the CDC 6600 and the 7600 computer. Because of the smaller amount of significance available on the IBM 360 model 65 computer, it was found necessary to use the actual hydrostatic pressure for the full cells rather than pseudopressures (generally zero) characteristic of the SMAC method to obtain adequate convergence of the iteration process. The convergence criteria for the SMAC iteration was defined as the maximum permitted change in pressure from hydrostatic pressure in any cell between iteration steps divided by the sum of the changes at the two iteration steps.

The University of Hawaii ZUNI code includes features for prescribing the particle velocity along the left boundary as a sinusoidal function of time

$$U = A \sin(B * \text{TIME}) \quad \text{and} \quad U = A(\sin(B * \text{TIME}))^2$$

where A for shallow water Airy waves is HC/D where H is wave height, C is wave speed, and D is depth; and B is $2\pi/T$ where T is the period. Special features of graphing, tape dump, and restart are also included in the University of Hawaii ZUNI code.

III. THE SHOALING RESULTS

The dimensions of the shoaling calculations with a continental slope of 1/15 ending in a shelf 500 m deep are sketched in Fig. 1.

A. Solitary Tsunamis

While single solitary like waves are not realistic models of tsunami waves, they are useful for demonstrating fundamental features of the flow and for checking the numerical results.

The waves were generated by prescribing as a function of time the velocity of water inflowing from the left boundary. The velocity in the X direction was prescribed as

$$U = 0.04666(\sin(0.004713*TIME))^2$$

where TIME is in seconds. In 4550 m deep water this results in a single wave above the surface with a height of approximately 1 m, a width of approximately 140,000 m, a shallow water speed of \sqrt{gD} or 210 m/sec, and a period of approximately 660 sec.

The computed wave surface profiles for the 140,000 m wide single wave interacting with a 1/15 continental slope, running along a 500 m deep continental shelf, and reflecting off a cliff are shown in Fig. 2. In Fig. 3 the profiles are shown for multiple waves.

As the wave proceeds up the continental slope, the wave period remains constant while the velocity decreases from approximately 210 to 70 m/sec, the wavelength decreases from approximately 140,000 to 47,000 m, the height increases from 0.95 to 1.6 m, and then slowly decreases, forming a complicated train of waves. Upon reflection from the right boundary, a wave 2.4 m high is formed which is approximately double the height of the wave before it arrived at the boundary.

The experimental and numerical results of solitary wave, vertical wall run-up of Street, Chan, and Fromm (4) show that at small values of wave height divided by depth, the slope of the wave run-up vs. wave height is almost 2.0.

The computed wave surface profiles for the 140,000 m wide single wave running up a 1/15 continental shelf to above still water level are shown in Fig. 4. The growth of the wave was compared with the experimental and theoretical results of Madsen and Mei (6) for solitary waves interacting with uneven bottoms. The results of Madsen and Mei shoal only to depths of 0.2 of the initial depth. Within this range their results are in reasonable agreement with the results shown in Figs. 2 and 3. The maximum height of the wave was 2.8 m or about 3 times the initial wave height of .95 m. This must be considered a lower limit, as the resolution of the calculation is inadequate to determine the maximum height.

One approach to this problem is to look only at the last 100 m of water and compress the scale of the calculation by 45. As input we will use a piston that will initially produce a wave of the height calculated in the previous problem at 100 m. As shown in Fig. 5, the wave height is about 1.8 m. The wave speed is closely approximated by \sqrt{gD} or 31.5 m/sec. For a single wave above the surface, the period is 660 sec and the wavelength is 20,800 m; for a sine wave, the period is 1320 sec and the wavelength is 41,600 m.

The calculation was performed with a mesh of 15 x 68 cells as before with a ΔX of 150, ΔY of 10, Δt of 0.5, convergence error of 0.002; and the 1/15 slope was started at the 42nd cell or at 6300 m. The depth was 101.1 m and $U = 0.567 \sin(0.004713 * \text{TIME})$. The wave profiles are shown in Fig. 6, and the maximum height of the wave is 3.47 m or about 1.9 times the 1.8 m wave height used initially in the calculation and 3.6 times the 0.95 wave height before any shoaling had occurred. The wave then flattens to a height of 2.75 ± 0.1 m over the width considered. This is close to the 2.8 value calculated by the less resolved calculation. This also explains the flat top observed upon reflection in the less resolved calculation. It is apparently a realistic average height for the cell size used, and the flat top over several cell widths is also apparently correct.

For a more realistic model of a tsunami, we used sine waves with a half height of 0.5 or 1 m, a period of 1320 or 660 sec, and wavelength of 280,000 or 140,000 m.

B. One Meter Half Height, 1320 Second Tsunamis

Using a piston velocity prescribed by

$$U = 0.04666 \sin(0.004713 * \text{TIME}) ,$$

a wave develops in 4550 m deep water of approximately 0.95 m half height, with a wavelength of approximately 280,000 m, a period of 1320 sec, and a speed of 210 m/sec. The wave is slightly dispersive as it proceeds up a constant depth channel.

The computed wave surface profiles are shown in Figs. 7 and 8 for the tsunami interacting with a 1/15 continental slope, running along a 500 m deep continental shelf and reflecting off a cliff. The profiles are similar to those shown in Figs. 2 and 3. The peak shoaling height is 1.6 m which decreases to 1.4 m before it reflects off the wall with maximum and minimum heights of 2.75, -3.4, +2.75 m.

The calculated wave surface profiles in Figs. 7 and 8 are shown in Figs. 9 and 10 along with the shallow water, long wave calculations using the SWAN code described in Appendix A for the identical model. The long wave results do not disperse in the deep channel, do shoal higher and steeper, and do not disperse as they run along the shallow channel. Experimental evidence that such waves should disperse in the shallow channel is given in reference (6). The wave that reflects from the wall in the SWAN calculation is higher and results in a reflected wave that is 20% higher.

Figure 11 shows the computed wave surface profiles as the tsunami interacts with a 1/15 continental slope. The maximum and minimum calculated are 2.83, -4.0, +3.76, -4.11, +4.04 m. So the maximum run-up does not result from shoaling of the first wave but from shoaling of the second or third wave. Such behavior has been observed for real tsunamis. We can now place an upper limit of tsunami wave growth from shoaling up a 1/15 continental slope of at least a factor of 4.0. As discussed earlier and shown in Fig. 6, the scale of the calculation is such that this should

be considered an average over the cell size used rather than the actual maximum values.

The computed wave surface profiles are shown in Figs. 12 and 13 for the tsunami interacting with a 1/15 continental slope, running along a 950 m deep continental shelf and reflecting off a cliff. The peak shoaling height is 1.5 m, which decreases to 1.32 m before it reflects off the wall with maximum and minimum heights of 2.56, -3.0, +2.48 m.

C. One Meter Half Height, 660 Second Tsunamis

Using a piston velocity prescribed by

$$U = 0.04666 \sin(0.009426 * \text{TIME}) ,$$

a wave develops in 4550 m deep water of approximately 0.86 m half height. The shorter wavelength wave is more dispersive than the longer one discussed in section B.

The computed wave surface profiles are shown in Fig. 14 for the tsunami interacting with a 1/15 continental slope, running along a 500 m deep continental shelf and reflecting off a cliff. The peak shoaling height is 1.4 m, which decreases to 0.68 m before it reflects off the wall to a first wave maximum of 1.15 m. Subsequent wave interactions result in much larger wave run-ups.

Figure 15 shows the computed wave surface profiles as the tsunami interacts with a 1/15 continental slope. The maximum and minimum calculated are +2.14, -3.56, +3.44, -3.9, +3.6 m. Again the upper limit of tsunami wave growth from shoaling is at least a factor of 4.0.

Figure 16 shows the surface wave profiles for a 1.8 m half height, 660 sec tsunami shoaling up a 1/15 slope from 101.1 m. Comparison with Fig. 6 shows that with the same height at 101 m, the smaller wavelength shoals to a higher level but for a shorter distance and time.

D. Half Meter Half Height, 660 Second Tsunamis

Using a piston velocity prescribed by

$$U = 0.02333 \sin(0.009426 * \text{TIME}) ,$$

a wave develops in 4550 m deep water of approximately 0.4 m half height.

The computed wave surface profiles are shown in Figs. 17 and 18 for the tsunami interacting with a 1/15 continental slope, running along a 500 m deep continental shelf and reflecting off a cliff. The peak shoaling height is 0.62 m, which disperses as it runs along the shelf to 0.28 m. The wave run-up heights are 0.4, -1.32, +1.10, 2.10, +1.10, -1.72 m.

Some of the calculated wave surface profiles in Figs. 17 and 18 are shown in Fig. 19 along with the shallow water, long wave calculations using the SWAN code for the identical model. The difference between the two calculations increases as the wave progresses, becoming different by a factor of two upon reflection from the wall. While it could be stated that this is an example where the long wave, shallow water assumptions lead to appreciable error, this is not necessarily true since we do not know the nature of tsunami waves well enough to determine if the tsunami model should be more like the long wave model or the one we used.

Since most tsunami waves that have been observed after travel across the ocean have periods longer than 10 minutes, it is tempting to postulate that this is because the shorter waves are so dispersive that they cannot propagate long distances.

Figure 20 shows the surface wave profiles as the tsunami interacts with a 1/15 continental slope. The maximum and minimum calculated are 0.91, -2.03, +1.5, -1.79, +1.68, -2.1, +1.54 m. Again the upper limit of the tsunami wave growth from shoaling is at least a factor of 4.0.

IV. THE UNDERWATER BARRIER RESULTS

A submerged barrier usually absorbs some of the wave energy by causing the wave to break prematurely and reflecting part of the wave energy back seaward. Tsunami waves are of sufficiently long wavelength that they do not break, so underwater barriers will be effective only as reflectors of the energy. The shallow water, long wave theory is inadequate to describe the effect of underwater barriers on tsunami waves because the vertical component of velocity is a crucial feature of the flow.

Johnson, Fuchs, and Morison (7) present results of an experimental investigation of the damping action of submerged rectangular breakwaters. They use the inshore wave height divided by the seaward wave height before interaction with the barrier as the transmission coefficient, and graph it against the dimensionless quantity of barrier height divided by channel water depth.

The calculations were performed assuming the barrier was located in 101.1 m of water and extended to within 21.1, 11.1, and 6.1 m of the still water surface. The wave height at 100 m of 1.8 m from Fig. 5 was assumed. The wave period assumed was 1320, 660, and, for a more detailed wave interaction calculation, a short period of 110 sec.

The 21.1 and 11.1 m deep barriers used the mesh described previously for Fig. 6. The barrier was 450 m wide, occupying cells 30 to 32 or from 4350 to 4800 m.

The 6.1 m deep barrier calculation was performed using a mesh of 23 x 45 cells with a ΔX of 150, ΔY of 5.0, Δt of 0.3, convergence error of 0.002; and the barrier was 450 m wide, occupying cells 20 to 22 or from 2850 to 3300 m.

The surface wave profiles for a 660 sec period tsunami interacting with barriers 21.1, 11.1, and 6.1 m below the water surface are shown in Figs. 21, 22, and 23. The initial inshore wave heights are 1.4, 1.1, and 0.54 m, respectively, for an undisturbed seaward height of 1.84 m. The 6.1 m height is so far below the seaward height that it is probably a lower limit value. The calculation was not used to later times as the wave height was being appreciably disturbed by the right boundary.

Figure 24 shows a comparison of the surface wave profiles shown in Fig. 22 with shallow water, long wave calculations. As expected, the long wave model is inadequate.

Figure 25 shows the surface wave profiles for a 1320 sec period tsunami interacting with a 11.1 m deep barrier. The initial inshore wave height is 1.03 m. This is probably a lower limit since the seaward height is significantly larger at the time the calculation was ended because it was being disturbed by the right boundary.

Figures 26, 27, and 28 show the surface wave profiles for a 110 sec period tsunami interacting with barriers 21.1, 11.1, and 6.1 m below the water surface. The initial inshore wave heights are 1.34, 1.046, and 0.35, respectively, for an undisturbed seaward height of 1.9 m.

The transmission coefficient as a function of the barrier height divided by depth is shown in Fig. 29. The experimental data from Figs. 4 and 5 of reference (7) and the tsunami curve of Fig. 29 are shown in Fig. 30. While the characteristics are quite different between the experimental and calculated waves, the effectiveness of the underwater barrier appears similar.

V. CONCLUSIONS

The detailed numerical simulation of gravity waves that resemble actual tsunami waves has been achieved for the first time. Realistic simulation of the interaction of tsunami waves with slopes that resemble the continental slope has been demonstrated. Wave heights were observed to increase by a factor of 4 as they shoaled up a 1/15 continental slope. The second or third wave often exhibited the highest wave run-up.

Similar results can be obtained using shallow water, long wave theory for long wavelength tsunamis, but fail to be adequate to describe the flow of tsunamis over underwater barriers.

Underwater barriers can reflect significant amounts of the tsunami energy. The shallow water, long wave theory is inadequate to describe the flow of tsunamis over underwater barriers.

The numerical simulation of tsunami waves has been demonstrated. The extension of the SMAC numerical technique to three dimensions has already been accomplished at Los Alamos Scientific Laboratory. Three-dimensional calculations of tsunami waves interacting with harbors, with multi-dimensional barriers, and with the ocean floor over the entire ocean are within the state of the art.

The numerical simulation of the formation of tsunamis by tectonic displacement in two and three dimensions could furnish considerable insight into the important characteristics of the process of tsunami generation.

ACKNOWLEDGEMENTS

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* with Joint Tsunami Research Effort, National Oceanic and Atmospheric Administration

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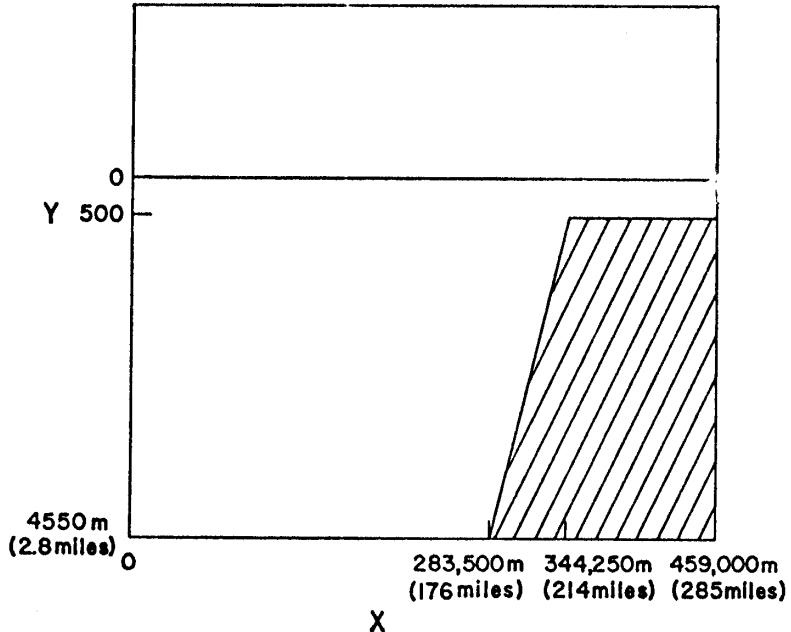


Fig. 1 - A sketch of the geometry of the calculation with the dimensions in meters and miles.

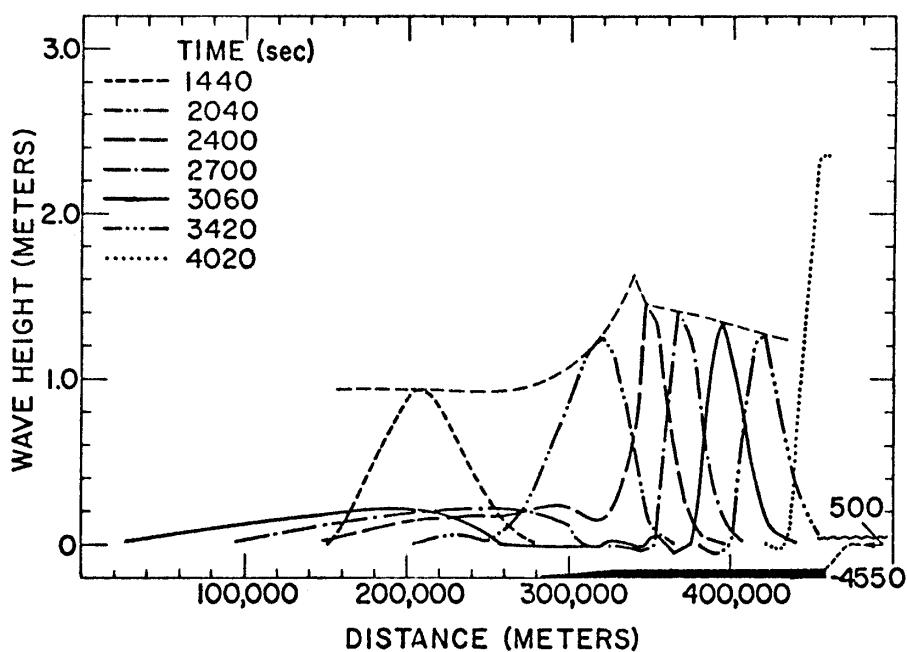


Fig. 2 - The computed wave surface profiles for the 140,000 m wide single wave interacting with a 1/15 continental slope (sketched on bottom of graph), a continental shelf 500 m deep and reflecting off a cliff.

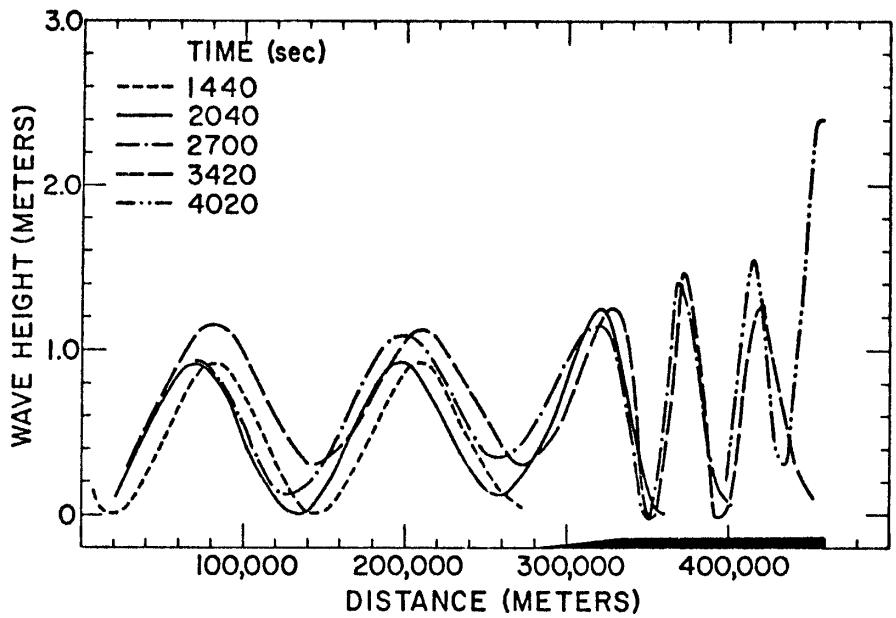


Fig. 3 - The computed wave surface profiles for multiple waves at various times for system in Fig. 2.

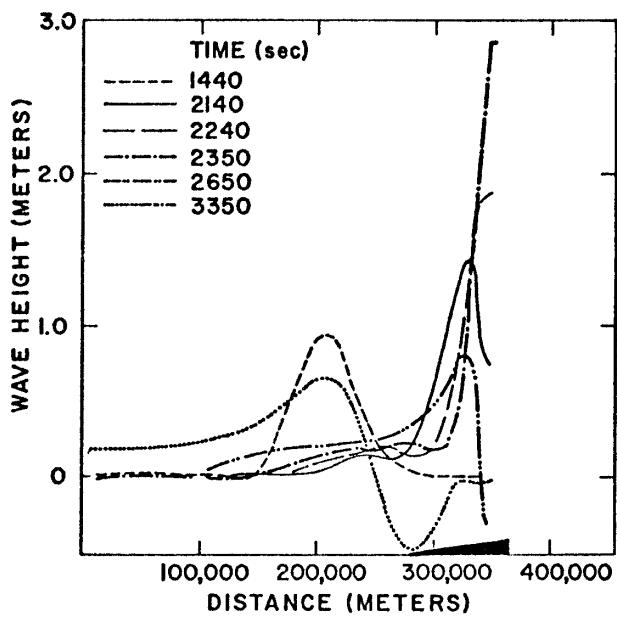


Fig. 4 - The computed wave surface profiles for a single wave interacting with a 1/15 continental shelf for system in Fig. 2.

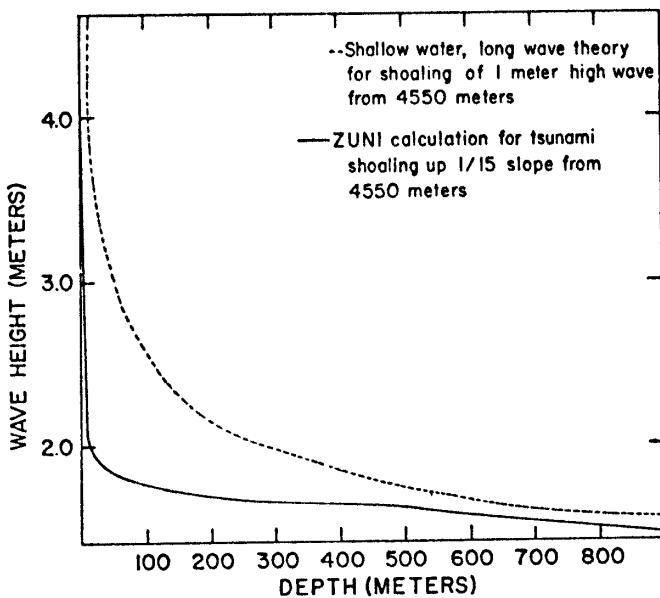


Fig. 5 - The amplitude of calculated 1 m half height, 1320 sec (or 1 m high, 660 sec single wave above surface) tsunami waves as they shoal up a 1/15 slope from 4550 m. Also shown is the shallow water, long wave curve.

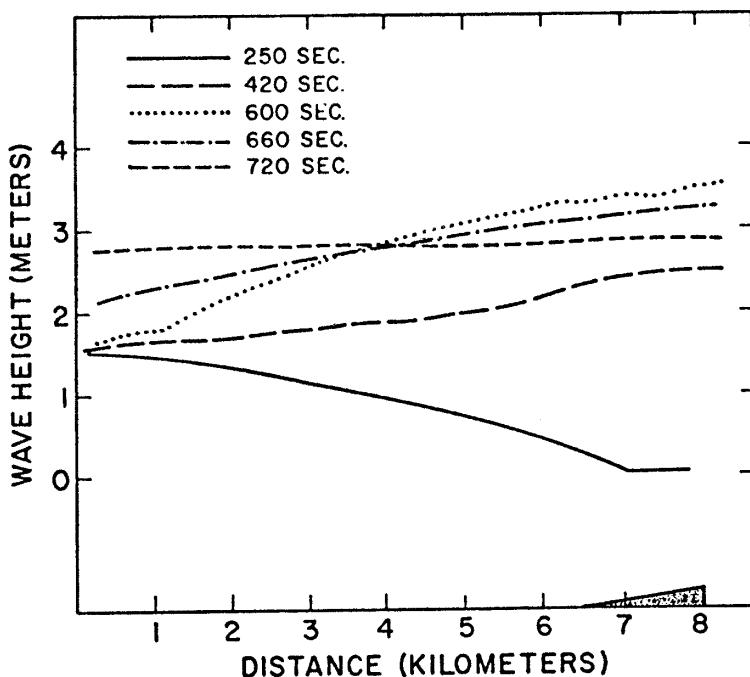


Fig. 6 - The computed wave surface profiles for a 1.8 m half height, 1320 sec tsunami shoaling up a 1/15 slope from 101.1 m.

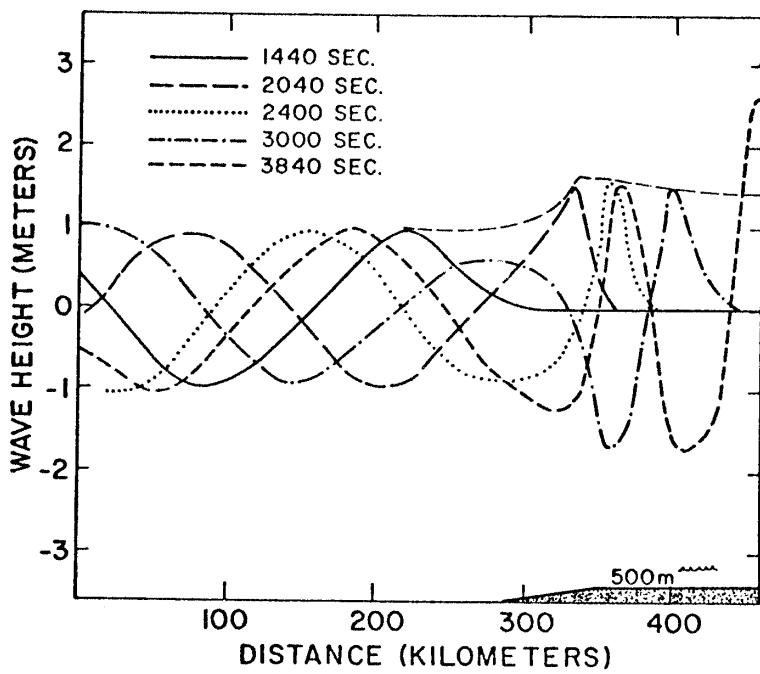


Fig. 7 - The computed wave surface profiles for a 1 m half height, 1320 sec tsunami interacting with a 1/15 continental slope, a continental shelf 500 m deep and reflecting off a cliff.

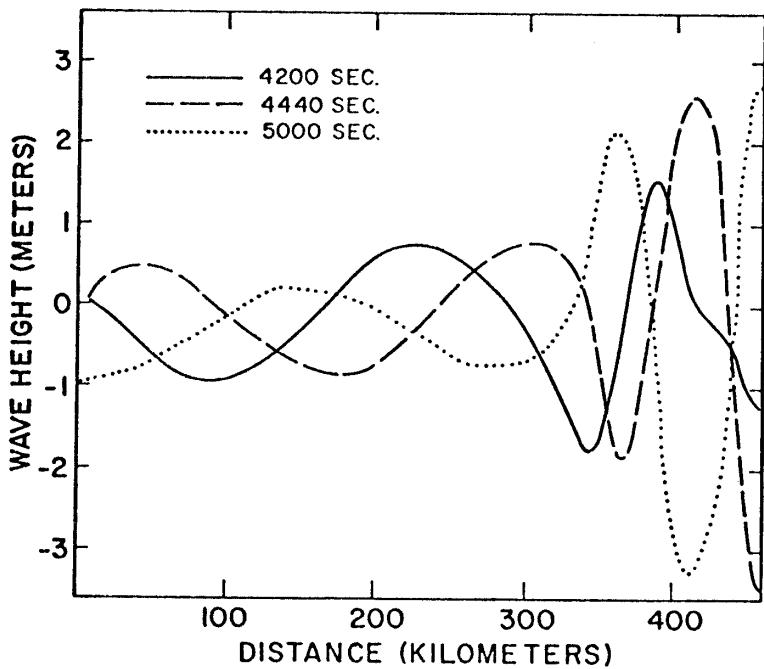


Fig. 8 - Continuation of Fig. 7.

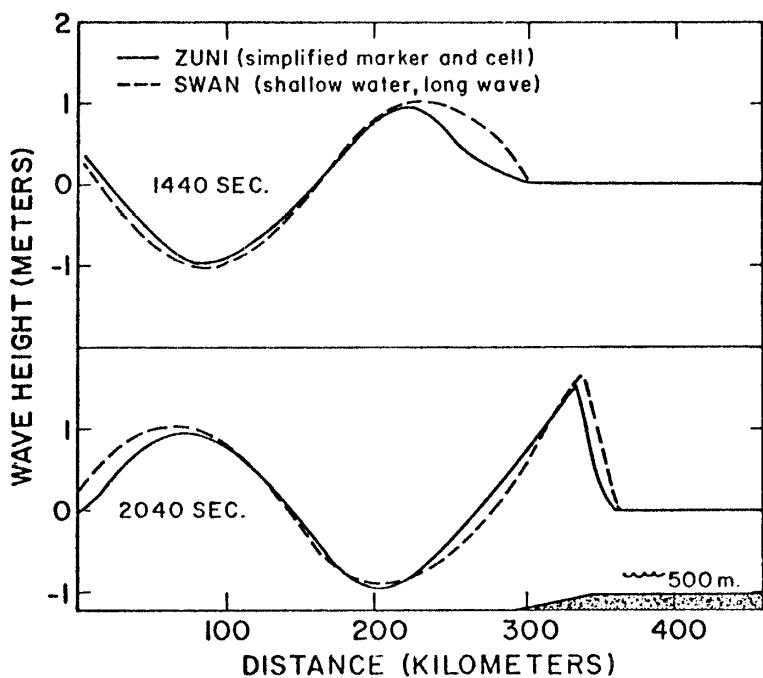


Fig. 9 - The wave profiles of Fig. 7 and shallow water, long wave calculations for the same model.

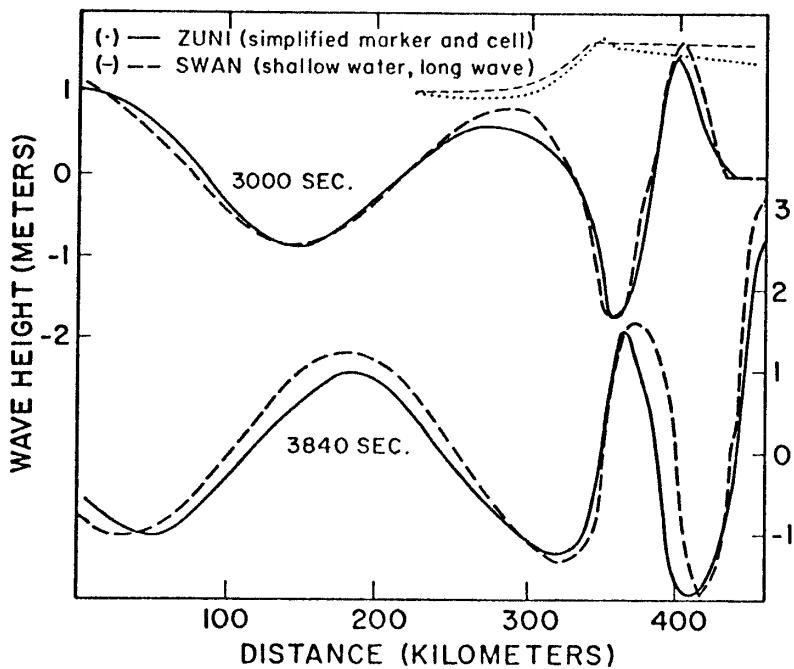


Fig. 10 - Continuation of Fig. 9.

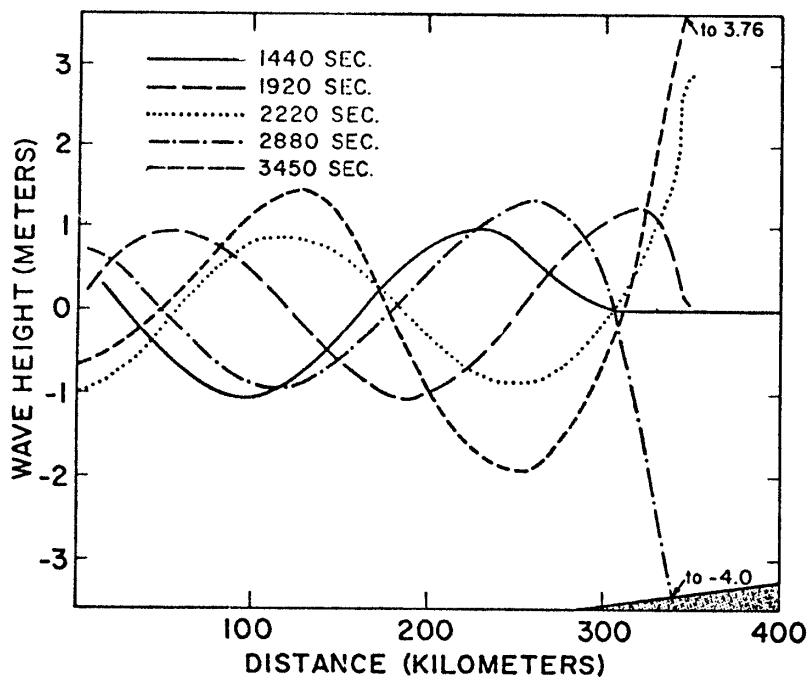


Fig. 11 - The computed wave surface profiles for the wave in Fig. 7 interacting with a 1/15 continental shelf.

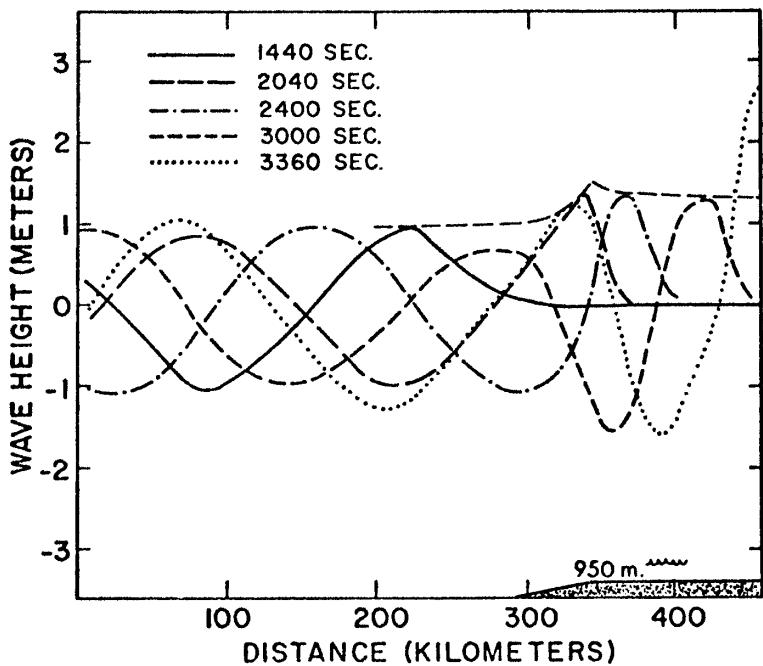


Fig. 12 - The computed wave surface profiles for a 1 m half height, 1320 sec tsunami interacting with a 1/15 continental slope, a continental shelf 950 m deep and reflecting off a cliff.

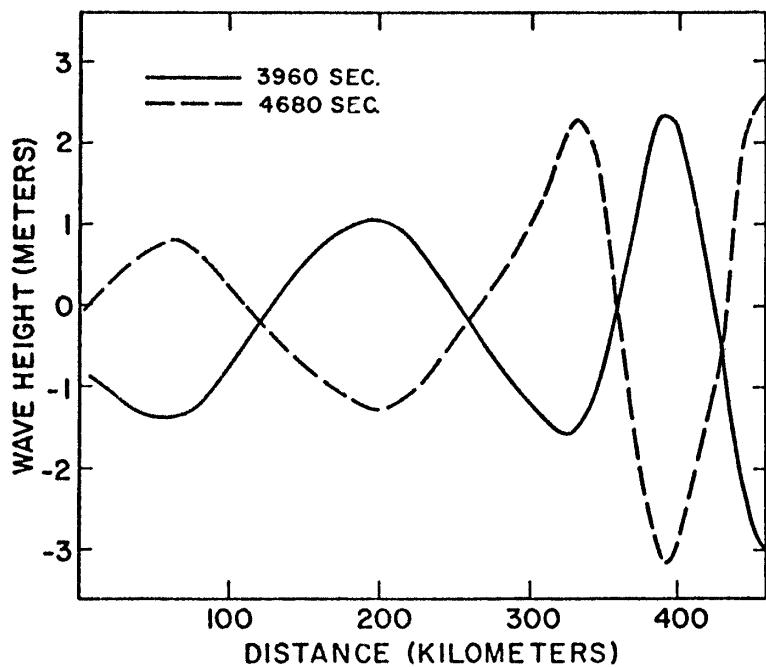


Fig. 13 - Continuation of Fig. 12.

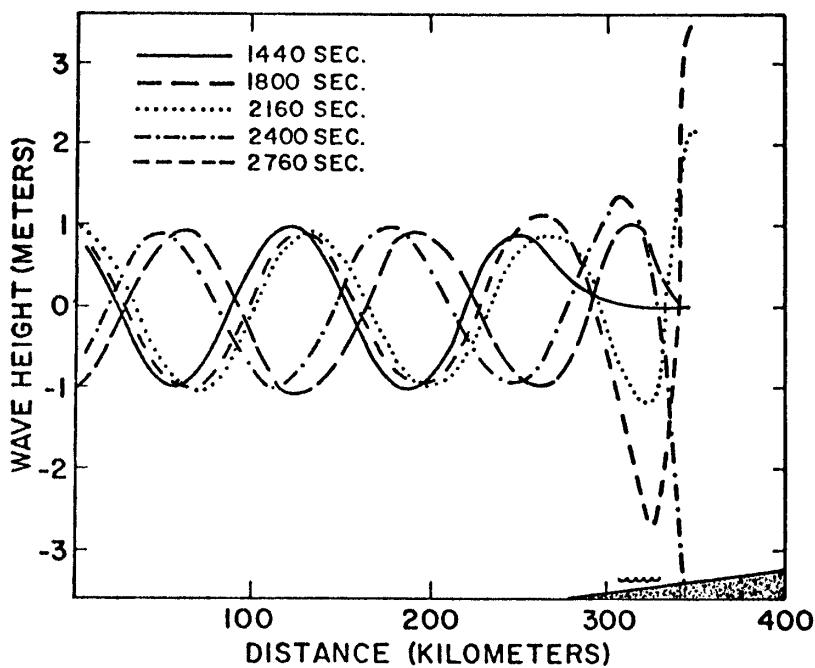


Fig. 14 - The computed wave surface profiles for a 1 m half height, 660 sec tsunami interacting with a 1/15 continental slope, a continental shelf 500 m deep and reflecting off a cliff.

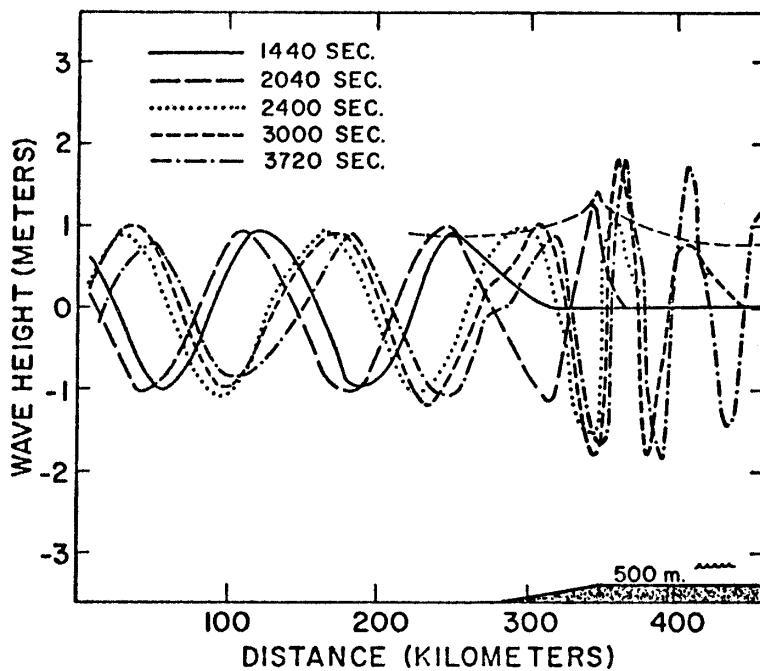


Fig. 15 - The computed wave surface profiles for the wave in Fig. 14 interacting with a 1/15 continental slope.

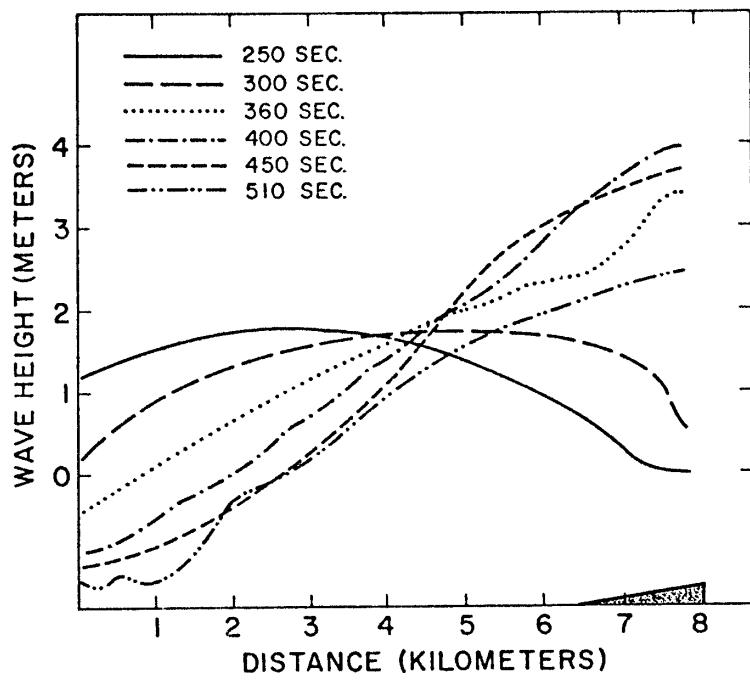


Fig. 16 - The computed wave surface profiles for a 1.8 m half height, 660 sec tsunami shoaling up a 1/15 slope from 101.1 m.

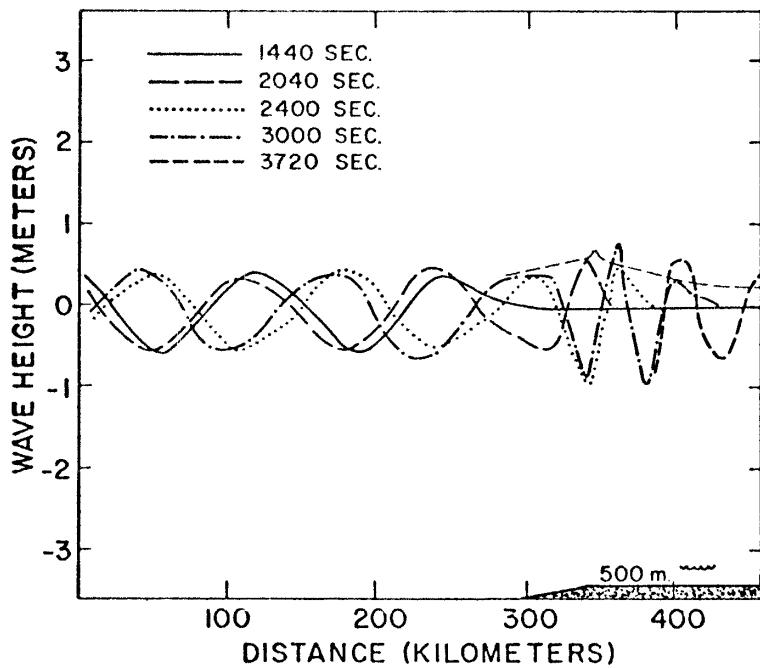


Fig. 17 - The computed wave surface profiles for a 0.5 m half height, 660 sec tsunami interacting with a 1/15 continental slope, a continental shelf 500 m deep and reflecting off a cliff.

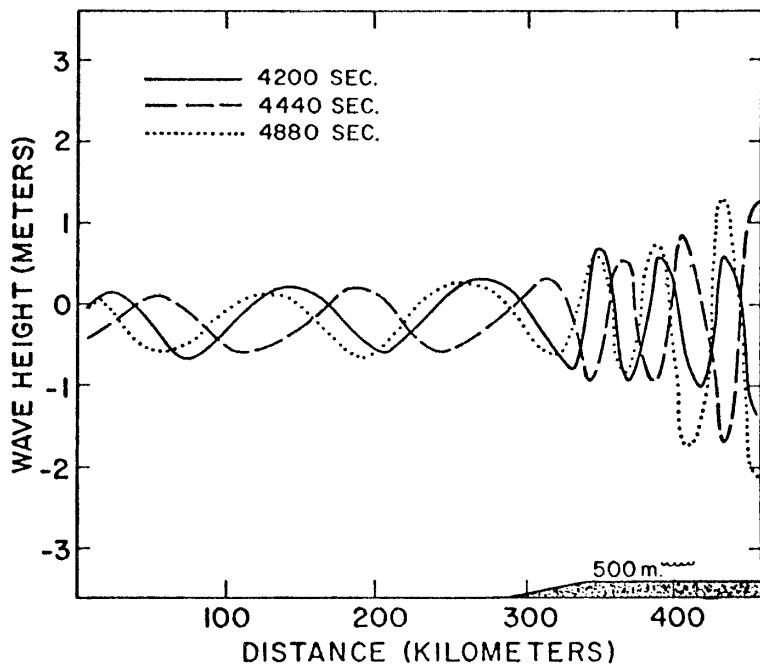


Fig. 18 - Continuation of Fig. 17.

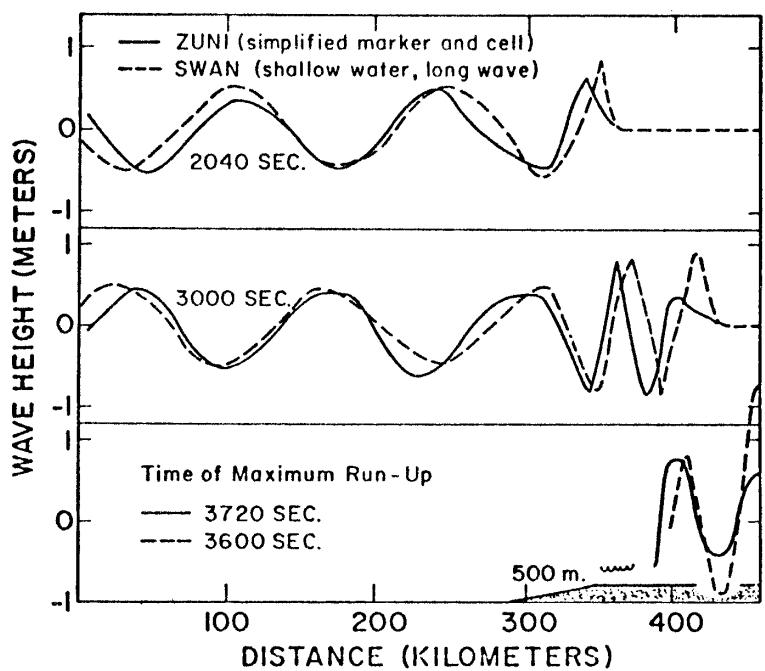


Fig. 19 - The wave profiles of Fig. 17 and shallow water, long wave calculations for the same model.

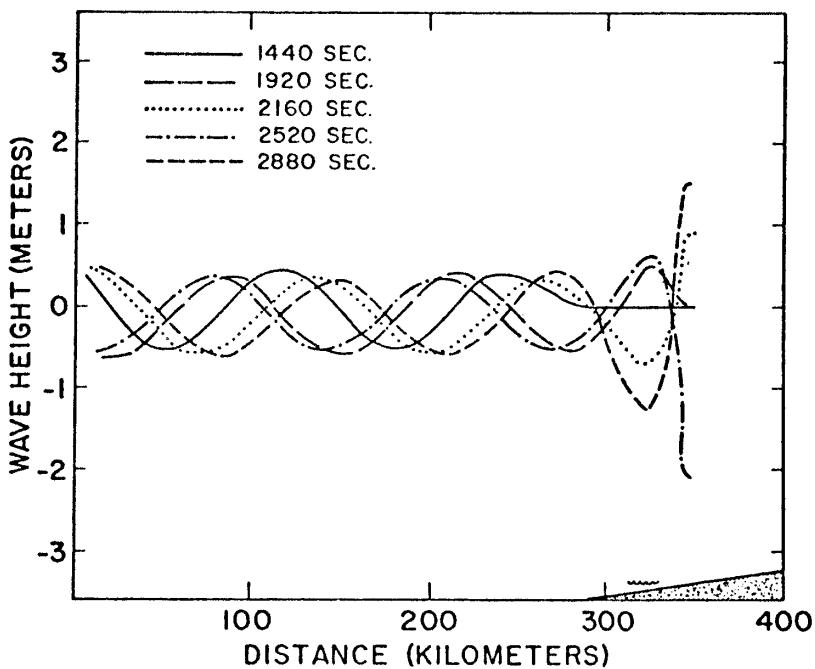


Fig. 20 - The computed wave surface profiles for the wave in Fig. 17 with a 1/15 continental slope.

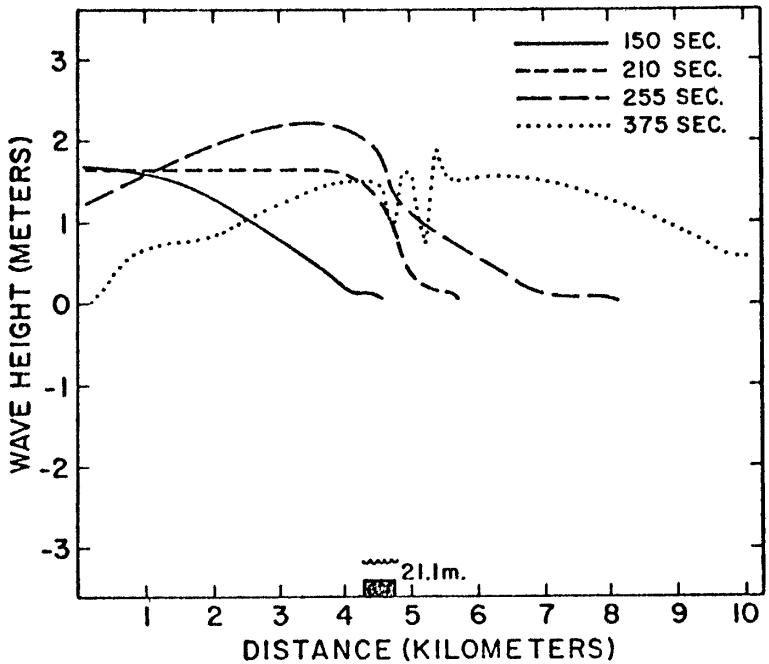


Fig. 21 - Surface wave profiles for a 660 sec tsunami interacting with a 21.1 m deep barrier.

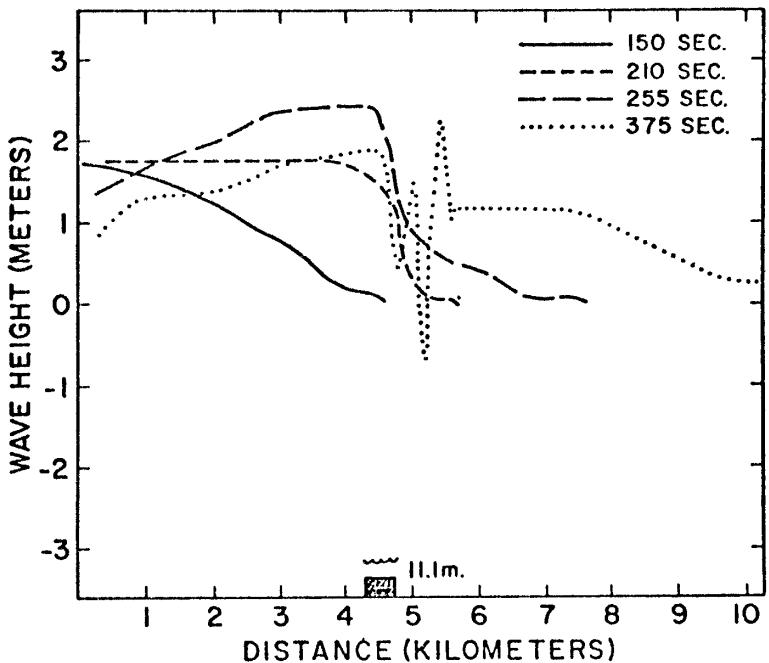


Fig. 22 - Surface wave profiles for a 660 sec tsunami interacting with a 11.1 m deep barrier.

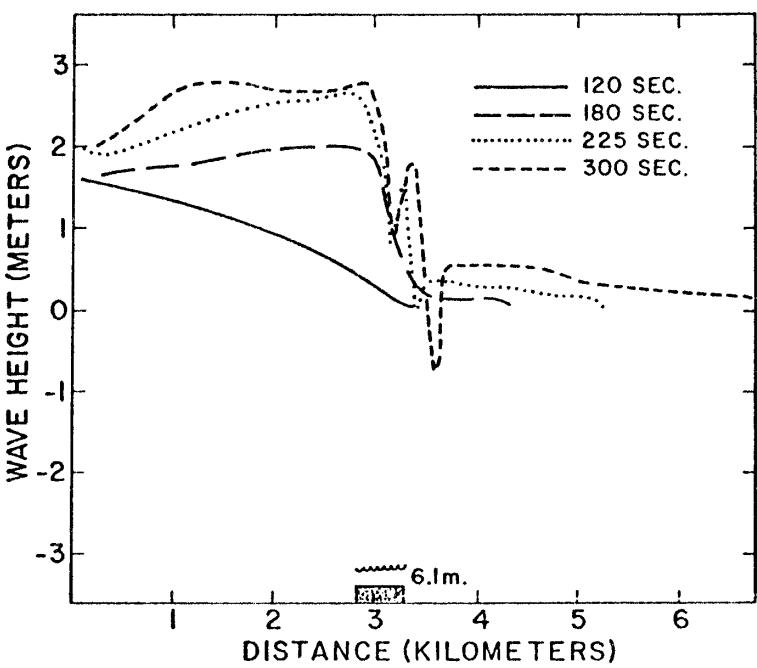


Fig. 23 - Surface wave profiles for a 660 sec tsunami interacting with a 6.1 m deep barrier.

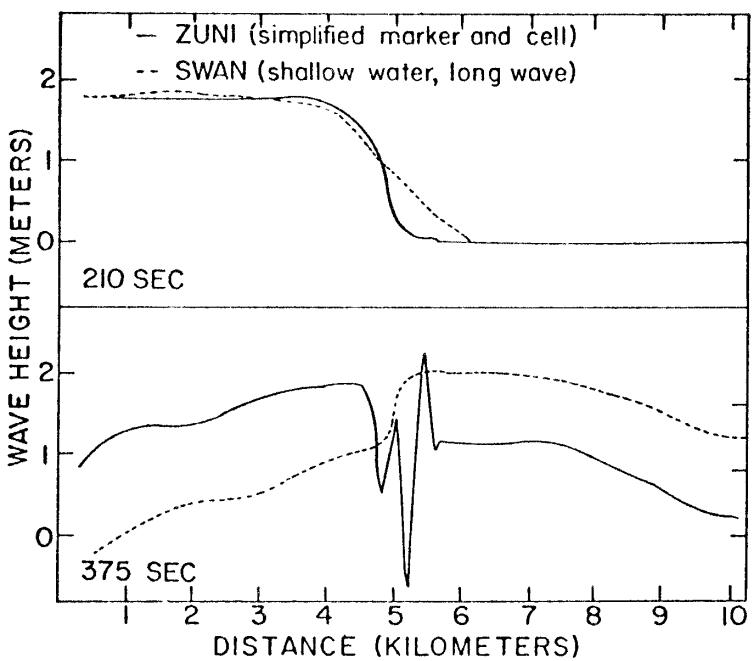


Fig. 24 - The surface wave profiles in Fig. 22 and the shallow water, long wave profiles for the same model.

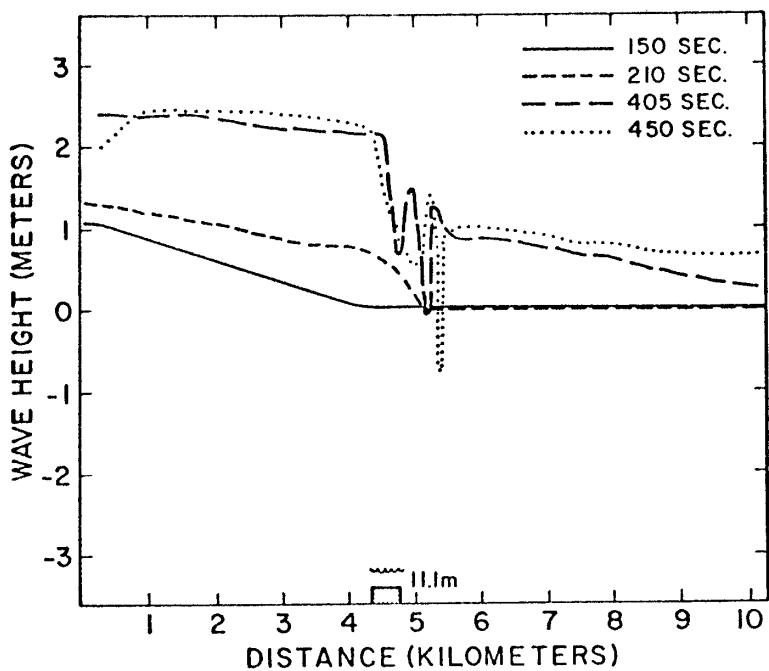


Fig. 25 - Surface wave profiles for a 1320 sec tsunami interacting with a 11.1 m deep barrier.

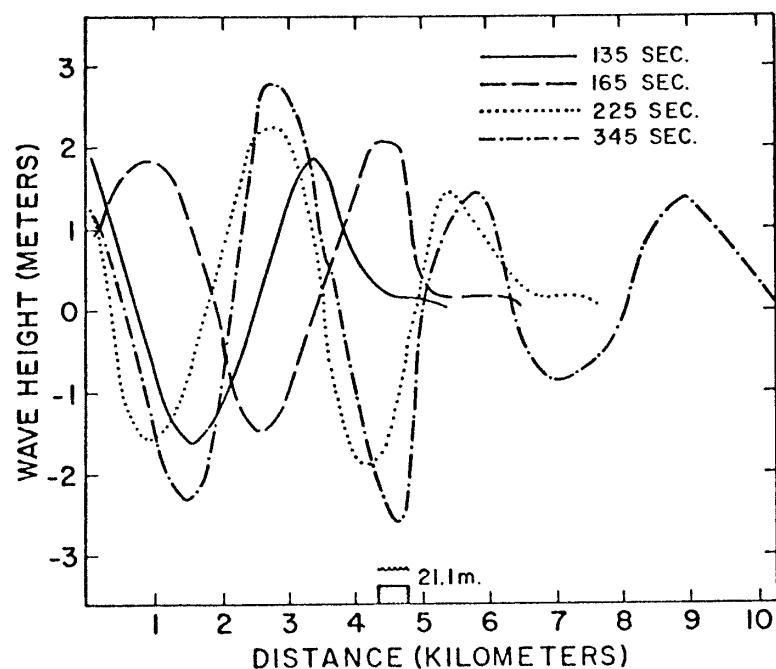


Fig. 26 - Surface wave profiles for a 110 sec tsunami interacting with a barrier 21.1 m below the water surface.

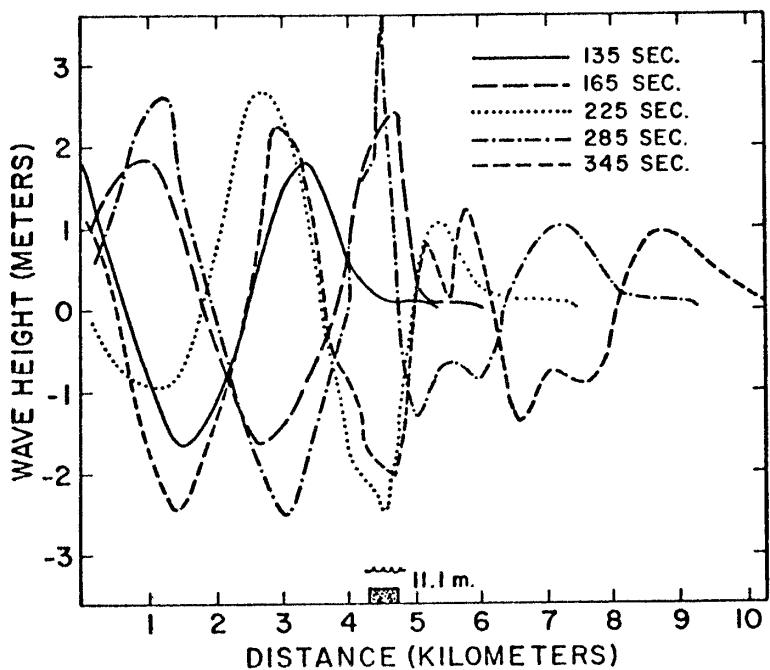


Fig. 27 - Surface wave profiles for a 110 sec tsunami interacting with a barrier 11.1 m below the water surface.

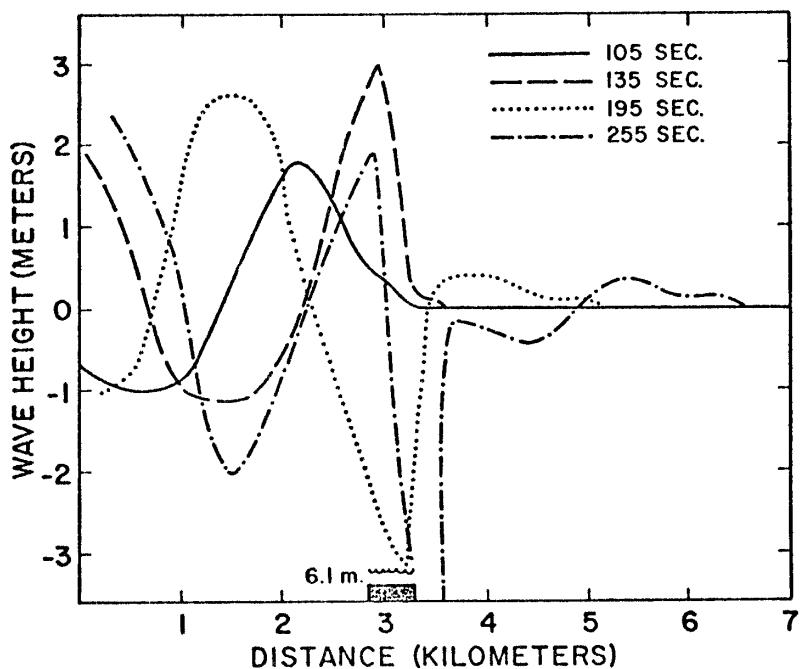


Fig. 28 - Surface wave profiles for a 110 sec tsunami interacting with a barrier 6.1 m below the water surface.

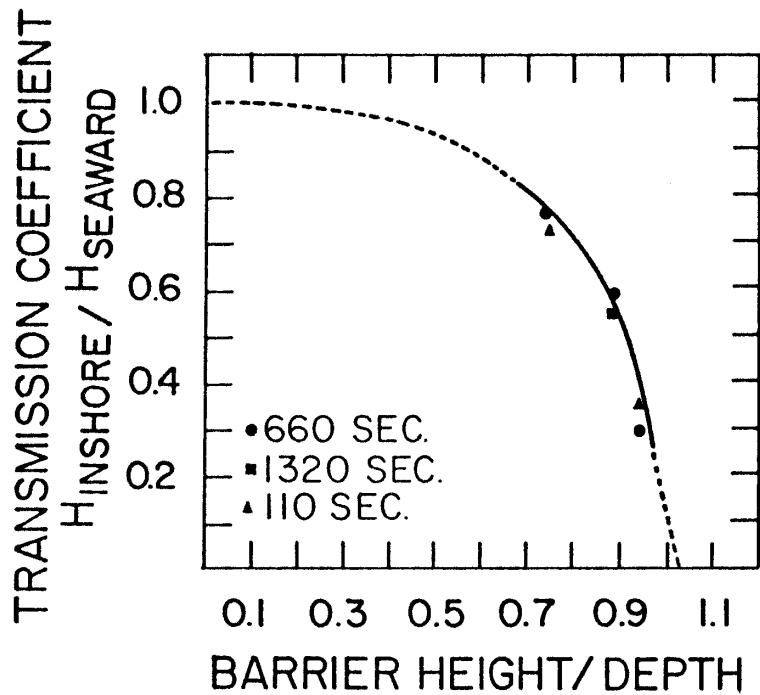


Fig. 29 - The calculated transmission coefficient of tsunami waves as a function of barrier height divided by depth.

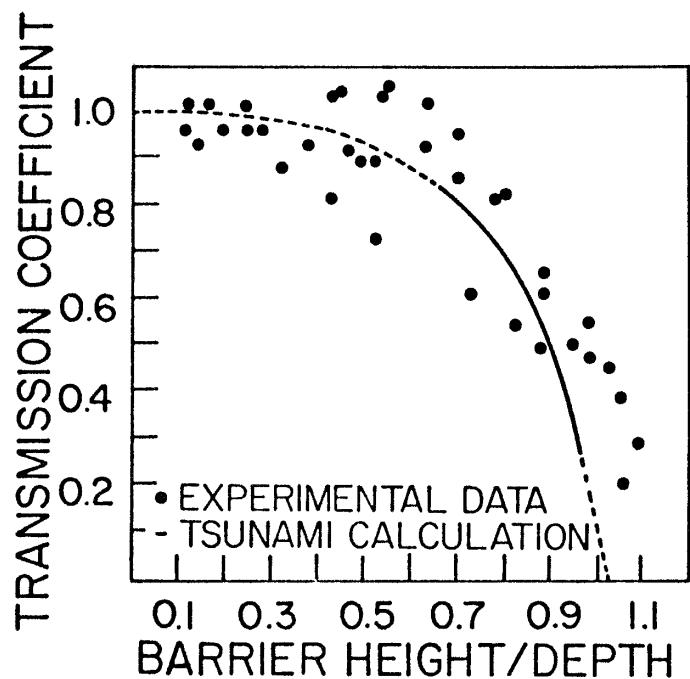


Fig. 30 - The Johnson, Fuchs, and Morison experimental submerged breakwater data and the calculated tsunami curve of Fig. 29.

APPENDIX A

SWAN: A Shallow Water, Long Wave Code

The long wave theory applies when the depth relative to the wavelength is small, and when the vertical component of motion does not influence the pressure distribution which is assumed to be hydrostatic. The long wave theory results in waves that become steeper as they move down a channel, that are too steep as they shoal and hence break too early. This is called the "long wave paradox" and is more serious as the distance and time of interest increases.

Numerical solution of the long wave equations have been attempted by many authors. The one described here is similar to the one described by Loomis (8). The long wave equations solved by the SWAN code are:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} + g \frac{\partial H}{\partial X} = FV + F^{(x)} - g \frac{U(U^2+V^2)^{1/2}}{C^2(D+H)}$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} + g \frac{\partial H}{\partial Y} = FU + F^{(y)} - g \frac{U(U^2+V^2)^{1/2}}{C^2(D+H)}$$

$$\frac{\partial H}{\partial t} + \frac{\partial(D+H-R)U}{\partial X} + \frac{\partial(D+H-R)V}{\partial Y} - \frac{\partial R}{\partial t} = 0$$

where

U = velocity in X direction (i index)

V = velocity in Y direction (j index)

g = gravity

t = time (n index)

H = wave height above mean water level

R = bottom motion

F = Coriolis parameter

C = coefficient of DeChezy for bottom stress

$F^{(x)}$, $F^{(y)}$ = forcing functions of wind stress and barometric pressure in X and Y direction

D = depth .

Using the "central difference" technique described by Loomis (8), the wave height H and depth D are taken as cell centered and the velocities are centered at cell boundaries. The difference equations used at each time step are in order:

$$\begin{aligned}
 H_{i,j}^{n+1} &= H_{i,j}^n - \Delta t \left[\frac{U_{i+1,j}^n}{\Delta X} \left(D_{i+1,j} + H_{i+1,j}^n - R_{i+1,j}^n \right) \right. \\
 &\quad \left. - \frac{U_{i,j}^n}{\Delta X} \left(D_{i,j} + H_{i,j}^n - R_{i,j}^n \right) \right. \\
 &\quad \left. + \frac{V_{i,j+1}^n}{\Delta Y} \left(D_{i,j+1} + H_{i,j+1}^n - R_{i,j+1}^n \right) \right. \\
 &\quad \left. - \frac{V_{i,j}^n}{\Delta Y} \left(D_{i,j} + H_{i,j}^n - R_{i,j}^n \right) \right] + R_{i,j}^{n+1} - R_{i,j}^n \\
 U_{i,j}^{n+1} &= U_{i,j}^n - \frac{\Delta t}{2} \left(\frac{U_{i,j}(U_{i+1,j} - U_{i-1,j})}{\Delta X} + \frac{V_{i,j}(U_{i,j+1} - U_{i,j-1})}{\Delta Y} \right) \\
 &\quad - g \frac{\Delta t}{\Delta X} \left(H_{i,j}^{n+1} - H_{i-1,j}^{n+1} \right) \\
 &\quad + \Delta t \left(-FV_{i,j}^n - F_{i,j}^{(x)} + S_{i,j}^B \right) \\
 V_{i,j}^{n+1} &= V_{i,j}^n - \frac{\Delta t}{2} \left(\frac{U_{i,j}(V_{i+1,j} - V_{i-1,j})}{\Delta X} + \frac{V_{i,j}(V_{i,j+1} - V_{i,j-1})}{\Delta Y} \right) \\
 &\quad - g \frac{\Delta t}{\Delta Y} \left(H_{i,j}^{n+1} - H_{i,j-1}^{n+1} \right) \\
 &\quad + \Delta t \left(FU_{i,j}^n - F_{i,j}^{(y)} + S_{i,j}^B \right)
 \end{aligned}$$

and

$$S_{i,j}^B = g U_{i,j}^n \left(\sqrt{U_{i,j}^{n-2}} + \sqrt{V_{i,j}^{n-2}} \right)^{1/2} / C^2 \left(D_{i,j} + H_{i,j}^n \right) .$$

Boundary conditions of piston, continuum, or reflective are available in the SWAN code. The problem mesh is surrounded by a layer of boundary cells whose H , U , and V are prescribed by setting the H of the boundary cell to the nearest neighbor for continuum or reflective boundaries and to the calculated value appropriate for the piston boundary. The appropriate U or V boundary velocity is calculated from the prescription for piston boundaries and is set to zero for reflective boundaries and to the nearest neighbor value for continuum boundaries.

The stability criterion requires that Δt be small enough such that a wave front may not pass through more than one cell in one time step.

While the "long wave paradox" is a severe limitation on the accuracy of the results, the code can be most useful and inexpensive if applied with caution to problems that are appropriate for the method.

APPENDIX B

WAVE: A Code to Calculate Airy, Stokes, and Solitary Waves

This appendix describes the results of a preliminary study to establish numerically the state values associated with tsunami waves assumed to behave as Airy or solitary waves. To accomplish this, a useful code was written called WAVE. The WAVE code uses the equations for Airy, third order Stokes and Laitone solitary gravity waves described in reference (9). It calculates the wave height as a function of wavelength; and the pressure, U velocity, and V velocity as a function of wavelength and depth. The calculations are performed for the right half of the wave but can be easily changed for any range of interest.

The Input

card 1	(format 18A4)	
	column 2-72	name of wave
card 2	(format 1X,I4)	
	column 2-5	0001 for Airy wave 0002 for solitary wave 0003 for Stokes wave
card 3	(format 4E18.11)	
	column 1-18	wave amplitude
	19-36	wave depth from still water level
	37-54	wavelength (ignored for solitary wave)
	55-72	density
card 4	(format E18.11)	
	column 1-18	acceleration due to gravity

Code Conventions

- For Airy waves: The wave amplitude is the half height where height is defined as the vertical distance between minimum and maximum of wave surface.
- For solitary waves: The wave amplitude is the maximum height above still water level.
- For Stokes waves: The wave amplitude is some value less than the half height characteristic of the first component of wave.

The units must be consistent.

For solitary waves the wave amplitude divided by depth should be less than 0.3. The wavelength used for the solitary wave is the length between approximately ± 0.05 maximum wave height since the total wavelength is infinite.

For Stokes waves the depth divided by the wavelength should be greater than 0.125 and less than approximately 2.0.

The FORTRAN listing of the WAVE code is shown on the following pages B3 through B7.

FORTRAN Listing of WAVE Code

- B3 -

```

FORTRAN IV G LEVEL 20          MAIN          DATE = 73019        15/28/49
0001      DIMENSION    X1(20),X2(20),P(400),DP(400),U(400),V(400),WH(400),
0001      1LABEL(18)
0001      2,Z(20),Y(20)
C      A # WAVE AMPLITUDE WHICH IS HALF HEIGHT FOR AIRY, HEIGHT FOR
C      SOLITARY AND AMPLITUDE FOR STOKES
C      H # WATER DEPTH WHICH IS CALLED D IN SOLITARY AND STOKES
C      WL#WAVE LENGTH
C      GZ#GRAVITY
C      RHC # DENSITY
C      INC IS 1 FOR AIRY
C      INC IS 2 FOR SOLITARY
C      INC IS 3 FOR STOKES
0002      DATA PI/3.14159/
0003      SCH2(DUM)=(1.-TANH(DUM)**2)
0004      100 READ 900,LABEL
0005      READ 902,INC
0006      READ 901,A,H,WL,RHC,GZ
0007      900 FFORMAT(18A4)
0008      901 FFORMAT(4E18.11)
0009      902 FFORMAT (1X,I4)
0010      GO TO(105,200,300),IND
C      GENERATE TABLES OF WAVE LENGTH AND DEPTHS
0011      105 CCNTINUE
0012      300 CCNTINUE
0013      X1(1)=0.
0014      DEL=0.05*WL
0015      DO 101 I=1,10
0016      X1(I+1)=X1(I)+DEL
0017      101 CCNTINUE
0018      I=I+1
0019      DEL=0.1*H
0020      X2(1)=-H
0021      DO 102 J=1,10
0022      X2(J+1)=X2(J)+DEL
0023      AM=-A
0024      IF(X2(J+1).GT.AM) GO TO 103
0025      102 CCNTINUE
0026      103 J=J+1
0027      X2(J)=-A
0028      X2(J+1)=-0.5*A
0029      X2(J+2)=0.0
0030      X2(J+3)=+0.5*A
0031      X2(J+4)=A
0032      J=J+4
0033      GO TO (104,200,301),IND
0034      104 CCNTINUE
C      CALCULATE CONSTANTS
0035      C=SQRT((GZ*WL*0.5/PI)*TANH(2.0*PI*H/WL))
0036      T=WL/C
0037      APCT=A*2.*PI/T
0038      RGA=RHC*GZ*A
0039      PHDL=2.*PI*H/WL
0040      CPHDL=COSH(PHDL)
0041      SPHDL=SINH(PHDL)
0042      PCL=2.*PI/WL
0043      TPHDL = 2.0*PHDL
0044      GV=0.5*C*(1.+TPHDL,SINH(TPHDL))
0045      EGY = 0.5*RHC*GZ*A*A
0046      N=]

```

```
0047      PRINT 911,L
0048      PRINT 923
0049      DO 110 K=1,I
0050      CPDLX1=COS(PDL*X1(K))
0051      SPDLX1=SIN(PDL*X1(K))
0052      WH(K)=A*CPDLX1+H
0053      DO 109 M=1,J
0054      CPDLX2=COSH(PDL*(X2(M)+H))
0055      SPDLX2=SIHN(PDL*(X2(M)+H))
0056      120 U(N)=APDT*CPDLX2*CPDLX1/SPHOL
0057      V(N)=APDT*SPDLX2*SPDLX1/SPHOL
0058      DP(N)=RCA*CPDLX2*CPDLX1/CPHOL
0059      P(N)=-RHO*GZ*X2(M)+DP(N)
0060      PRINT 922,X1(K),X2(M),WH(K),U(N),V(N),DP(N),P(N)
0061      IF(P(N).LT.0.0) P(N)=0.0
0062      IF(P(N).EQ.0.0) U(N)=0.0
0063      IF(P(N).EQ.0.0) V(N)=0.0
0064      IF(P(N).EQ.0.0) DP(N)=0.0
0065      N=N+1
0066      109 CONTINUE
0067      110 CONTINUE
C      GENERAL PRINT
0068      206 CONTINUE
0069      N=I-1
0070      GC TO (180,280,380),IND
0071      180 CONTINUE
0072      PRINT 911,LABEL
0073      GG TO 281
0074      280 PRINT 931,LABEL
0075      GG TO 281
0076      380 PRINI 933,LABEL
0077      281 CCNTINUE
0078      PRINT 912,A,H,WL
0079      PRINT 913,C,T,GZ
0080      IF(IND.EQ.1) PRINT 924,GV,EGY
0081      IF(IND.FQ.3) PRINT 925,SH
0082      PRINT 914
0083      NS=J
0084      DO 125 K=1,J
0085      NSP=I*(J-1)+NS
0086      PRINT 920,X2(J-K+1),(P(NT),NT=NS,NSP,J)
0087      NS=NS-1
0088      125 CONTINUE
0089      PRINT 920,X1(1),(X1(NA),NA=1,I)
0090      PRINT 918
0091      PRINT 915
0092      NS=J
0093      DO 121 K=1,J
0094      NSP=I*(J-1)+NS
0095      PRINT 920,X2(J-K+1),(U(NT),NT=NS,NSP,J)
0096      NS=NS-1
0097      121 CONTINUE
0098      PRINT 920,X1(1),(X1(NA),NA=1,I)
0099      PRINT 918
0100      PRINT 916
0101      NS=J
0102      DO 122 K=1,J
0103      NSP=I*(J-1)+NS
0104      PRINT 920,X2(J-K+1),(V(NT),NT=NS,NSP,J)
0105      NS=NS-1
0106      122 CONTINUE
0107      PRINT 920,X1(1),(X1(NA),NA=1,I)
0108      PRINT 918
0109      PRINT 917
```

```
0110      NS=J
0111      DO 123 K=1,J
0112      NSP=I*(J-1)+NS
0113      PRINT 920,X2(J-K+1),(DP(NT),NT=NS,NSP,J)
0114      NS=NS-1
0115 123  CONTINUE
0116      PRINT 920,X1(1),(X1(NA),NA=1,I)
0117      PRINT 918
0118      PRINT 919
0119      DO 124 NP=1,I
0120      PRINT 921,X1(NP),WF(NP)
0121 124  CONTINUE
0122      GO TO 100
0123      911  FORMAT (28H1 AIRY WAVE CALCULATION FOR ,18A4)
0124      912  FORMAT (/,14H AMPLITUDE   ,1PE11.4, 8H DEPTH   ,1PE11.4,15H WAVE
1 LENGTH ,1PE11.4)
0125      913  FORMAT(/,13H WAVE SPEED  1PE11.4, 9H PERIOD  ,1PE11.4,11H GRAVITY
1 ,1PE11.4)
0126      914  FORMAT (/, 24H1 DEPTH          PRESSURE )
0127      915  FORMAT (/, 24H1 DEPTH          U VELOCITY )
0128      916  FORMAT (/, 24H1 DEPTH          V VELOCITY )
0129      917  FORMAT (/, 24H1 DEPTH          DEL PRESSURE )
0130      918  FORMAT (24H          WAVE LENGTH )
0131      919  FORMAT (/, 25H1  WAVE LENGTH     HEIGHT)
0132      920  FORMAT(12(1X,1PE9.2))
0133      921  FORMAT(2(1PE12.11))
0134      922  FORMAT (7(1X,1PE16.9))
0135      923  FORMAT (118H          LENGTH          DEPTH          WAVE HEIGHT
1 U VELOCITY      V VELOCITY      DELTA PRESS      PRESSURE )
0136 924  FORMAT(/,17H GROUP VELOCITY ,1PE11.4,26H ENERGY PER SURFACE AREA
1 ,1PE11.4)
0137 925  FORMAT (/,13H WAVE HEIGHT ,1PE11.4)
0138 931  FORMAT (40H1 LAITONE SOLITARY WAVE CALCULATION FOR ,18A4)
0139 932  FORMAT (53H***** F/D TCO LARGE ****VELOCITIES WILL BE INCORRECT)
0140 933  FORMAT (42H1 STOKES THIRD CRDRE WAVE CALCULATION FOR ,18A4)
0141 934  FORMAT (43H***C/L TCO SMALL***STOKES THEORY INCORRECT)
C   SOLITARY WAVE
C   SWITCH H AND A SYMBOLS
0142 200  CONTINUE
0143      D=F
0144      H=A
0145      HCD=H/F
0146      SGD=SQRT(GZ*D)
0147      C=SGD*(1.+0.5*HDD-3.*HDD*HDD/20.)
C   ESTIMATE WAVE LENGTH AND PERIOD
C   ESTIMATE MADE FOR HALF WAVE LENGTH
0148      WL=2.*D/(SQRT(0.75*HDD)*(1.-5.*HDD/8.))
0149      T=WL/C
C   GENERATE WAVE LENGTH TABLES
0150      X1(1)=0.
0151      Z(1)=0.
0152      DEL=0.1*WL
0153      ZC=(SQRT(0.75*HDD))*(1.-(5./8.)*HDD)/D
0154      DO 201 I=1,10
0155      X1(I+1)=X1(I)+DEL
0156      Z(I+1)=X1(I+1)*ZC
0157 201  CONTINUE
0158      I=I+1
C   GENERATE DEPTHS & Y<
0159      DEL=0.1*D
```

```
0160      Y(1)=0.
0161      DC 202 J=1,10
0162      Y(J+1)=Y(J)+DEL
0163      X2(J+1)=Y(J+1)
0164 202  CONTINUE
0165      J=J+1
0166      Y(J)=D+0.2*M
0167      Y(J+1)=0.4*M+D
0168      Y(J+2)=0.6*M+D
0169      Y(J+3)=0.8*M+D
0170      Y(J+4)=M+D
0171      J=J+4
0172      DO 207 KP=1,J
0173      X2(KP)=D-Y(KP)
0174 207  CONTINUE
0175      N=1
0176      PRINT 931,LABEL
0177      PRINT 923
0178      DO 203 K=1,I
0179      SQZ=SCH2(Z(K))
0180      WH(K)=D+H*SQZ-0.75*M*H*D*SQZ*(1.-SQZ)
0181      DO 204 M=1,J
0182      YDS=(Y(M)/D)**2
0183      YDD=Y(M)/D
0184      U(N)=SGD*H*D*(1.+0.25*M*H*D*YDS)*SQZ+H*D*(-1.+9.*YDS/4.)*
1SQZ*SQZ
0185      V(N)=SGD*SQRT(3.)*SQRT(H*D**3)*YDD*SQZ*TANH(Z(K))*(1.-3.*H*D/8.-
10.5*M*H*D*YDS+H*D*(-2.+1.5*YDS)*SQZ)
0186      P(N)=RHO*GZ*(WH(K)-Y(M))-0.75*M*H*D*(2.*(YDD-1.)*(YDD-1.)**2)*
1(2.*SQZ-3.*SQZ*SQZ)
0187      IF(P(N).LT.0.0) P(N)=0.0
0188      DP(N)=P(N)-RHO*GZ*(D-Y(M))
0189      PRINT 922, Z(K), Y(M), WH(K), U(N), V(N), DP(N), P(N)
0190      IF(CP(N).LT.0.0) DP(N)=0.0
0191      IF(P(N).EQ.0.0) U(N)=0.0
0192      IF(P(N).EQ.0.0) V(N)=0.0
0193      IF(P(N).EQ.0.0) DP(N)=0.0
0194      N=N+1
0195 204  CONTINUE
0196 203  CONTINUE
0197      IF(T>0.3) PRINT 932
C      WAVE LENGTH AND PERIOD CHANGED FOR FULL WAVE
0198      WL=2.0*WL
0199      T=2.0*I
0200      A=H
0201      H=D
0202      GC TO 206
C      STCKES THIRD CRCR WAVE
0203 301  D=F
C      CALCULATE CONSTANTS
0204      TPDL=2.*PI*D/WL
0205      FPCL=2.*TPDL
0206      TDL1=TANH(TPDL)
0207      SDL1=SINH(TPDL)
0208      SDL2=SDL1*SDL1
0209      SDL3=SDL2*SDL1
0210      SDL4=SDL3*SDL1
0211      SCL5=SDL4*SDL1
0212      SCL6=SCL5*SDL1
0213      SDL7=SDL6*SDL1
0214      CDL1=CCSH(TPDL)
0215      CDL2=CDL1*CCL1
0216      CDL6=CDL2*CDL2*CCL2
0217      CFDL1=COSH(FPCL)
0218      CFDL2=CFDL1*CFDL1
0219      TPI=2.*PI
0220      AL=2.*PI*A/WL
```

```
0221      AL2=AL*AL
0222      AL3=AL2*AL
0223      F1=AL/SDL1-AL2*(1.+5.*CDL2)*CDL2/(8.*SDL5)
0224      F2=0.75*AL2/SDL4
0225      F3=(3./64.)*AL3*(11.-2.*CFCL1)/SDL7
0226      C=SQRT((GZ*WL/TPI)*TANH(TPDL*(1.+((PI*A/WL)**2)*(14.+4.*CFDL2)-
1(16.*SDL4))))
0227      T=WL/C
0228      TPL=TPI/WL
0229      FPL=2.*TPL
0230      SPL=3.*TPL
0231      PL=PI/WL
0232      A2=A*A
0233      A3=A2*A
0234      SH IS STOKES WAVE HEIGHT
0235      SH=2.*A+2.*PL*PL*A3*(3./16.)*(1.+8.*CDL6)/SDL6
0236      N=1
0237      PRINT 933,LABEL
0238      PRINT 923
0239      DO 310 K=1,I
0240      CTX=COS(TPL*X1(K))
0241      CFX=COS(FPL*X1(K))
0242      CSX=COS(SPL*X1(K))
0243      STX=SIN(TPL*X1(K))
0244      SFX=SIN(FPL*X1(K))
0245      SSX=SIN(SPL*X1(K))
0246      WH(K)=A*CTX+(PL*A2*(2.+CFDL1)*CDL1/(2.*SDL3))*CFX
1+(PL*PL*A3*(3./16.)*(1.+8.*CDL6)/SDL6)*CSX + C
0247      DO 309 M=1,J
0248      CSPLY=COSH(SPL*(X2(M)+C))
0249      SSPLY=SINH(SPL*(X2(M)+C))
0250      CPDLY=COSH(TPL*(X2(M)+C))
0251      SPDLY=SINH(TPL*(X2(M)+C))
0252      CFPLY=COSH(FPL*(X2(M)+C))
0253      SFPLY=SINH(FPL*(X2(M)+C))
0254      U(N)=C*(F1*CPDLY*CTX+F2*CFPLY*CFX+F3*CSPLY*CSX)
0255      V(N)=C*(F1*SPDLY*STX+F2*SFPLY*SFX+F3*SSPLY*SSX)
DP(N)=SH*0.5*CPDLY*CTX/CDL1+(3./8.)*SH*SH*PL*TDL1/SDL2
1*(CFPLY/SDL2-1./3.)*CFX-SH*(1./8.)*PI*TDL1*CFPLY/(WL*SDL2)
0256      DP(NJ=RHC*GZ*CP(N)
0257      P(N)=RHO*GZ*X2(M) + DP(N)
0258      PRINT 922,X1(K),X2(M),WH(K),U(N),V(N),DP(N),P(N)
0259      IF(P(N).LT.0.0) P(N)=0.0
0260      IF(P(N).EQ.0.0) U(N)=0.0
0261      IF(P(N).EQ.0.0) V(N)=0.0
0262      IF(P(N).EQ.0.0) DP(N)=0.0
0263      N=N+1
0264      309 CONTINUE
0265      310 CONTINUE
0266      DDL=D/WL
0267      IF(DDL.LT.0.125) PRINT 934
0268      H=C
0269      GC 10 206
0270      END
```

The results of solitary and Airy tsunami wave calculations are presented in Tables 1 through 10 for the following waves. Gravity is 9.8 m/sec².

Table	Type	Amplitude	Depth	Wavelength	Comment
1	solitary	0.5	4550	2.0×10^6	
2	solitary	1.0	4550	1.4×10^6	
3	Airy	0.5	4550	140,000	
4	Airy	0.5	4550	280,000	
5	Airy	1.0	4550	140,000	
6	Airy	1.0	4550	280,000	
7	Airy	1.8	100	21,000	shoaled with 140,000 m initial wavelength **
8	Airy	1.8	100	42,000	shoaled with 280,000 m initial wavelength
9	Airy	1.6	500	46,500	shoaled with 140,000 m initial wavelength
10	Airy	1.6	500	93,000	shoaled with 280,000 m initial wavelength

** assumed period remained constant and height as calculated using ZUNI code

Table 1

DEPTH	U	VELOCITY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-5.00E-01	2.33E-02	2.24E-02	1.99E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-3.98E-01	2.33E-02	2.24E-02	1.99E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-2.97E-01	2.33E-02	2.24E-02	1.99E-02	1.65E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.99E-01	2.33E-02	2.24E-02	1.99E-02	1.65E-02	1.30E-02	9.76E-03	0.0	0.0	0.0	0.0	0.0	0.0
-9.77E-02	2.33E-02	2.24E-02	1.99E-02	1.65E-02	1.30E-02	9.76E-03	7.08E-03	5.02E-03	0.0	0.0	0.0	0.0
4.55E-02	2.32E-02	2.23E-02	1.99E-02	1.65E-02	1.30E-02	9.75E-03	7.08E-03	5.02E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
9.10E-02	2.32E-02	2.23E-02	1.99E-02	1.65E-02	1.30E-02	9.75E-03	7.08E-03	5.02E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
1.37E-03	2.32E-02	2.23E-02	1.99E-02	1.65E-02	1.30E-02	9.75E-03	7.08E-03	5.02E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
1.82E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.08E-03	5.02E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
4.28E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.08E-03	5.01E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
2.73E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.07E-03	5.01E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
3.19E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.07E-03	5.01E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
3.64E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.07E-03	5.01E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
4.10E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.07E-03	5.01E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
4.55E-03	2.32E-02	2.23E-02	1.98E-02	1.65E-02	1.30E-02	9.74E-03	7.07E-03	5.01E-03	3.49E-03	2.40E-03	1.64E-03	1.64E-03
0.0	0.0	1.00E-05	2.00E-05	3.01E-05	4.01E-05	5.01E-05	6.01E-05	7.02E-05	8.02E-05	9.02E-05	1.00E-06	1.00E-06

Table 2

Table 3

```

AIRY WAVE CALCULATION FOR AIRY TSUNAMI

AMPLITUDE      5.0000E-01 DEPTH     4.5500E 03 WAVE LENGTH    1.4000E 05
WAVE SPEED     2.0971E 02 PERIOD    6.6757E 02 GRAVITY     9.8000E 00
GROUP VELOCITY   2.0686E 02 ENERGY PER SURFACE AREA   1.2250E 00

WAVE LENGTH      HEIGHT
0.0             4.55050000000E 03
6.9999609375E 03 4.55047265625E 03
1.3999921875E 04 4.5504234375E 03
2.0999882813E 04 4.55C29296875E 03
2.7999843750E 04 4.55015234375E 03
3.4999804688E 04 4.55000000000E 03
4.1999765625E 04 4.5498437500F 03
4.8999726563E 04 4.5497631250E 03
5.5999968750E 04 4.5495937500E 03
6.2999964843E 04 4.54952343750E 03
6.9999337500E 04 4.54950000000E 03

```

DEPTH	PRESSURE										
5.00E-01	2.19E-05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2.50E-01	2.45E 00	2.21E 00	1.51E 00	4.30E-01	0.0	0.0	0.0	0.0	0.0	0.0	
0.0	4.90E 00	4.66E 00	3.96E 00	2.88E 00	1.51E 00	1.56E-05	0.0	0.0	0.0	0.0	
-2.50E-01	7.35E 00	7.11E 00	6.41E 00	5.33E 00	3.96E 00	2.45E 00	9.36E-01	0.0	0.0	0.0	
-5.00E-01	9.80E 00	9.56E 00	8.86E 00	7.78E 00	6.41E 00	4.90E 00	3.39E 00	2.02E 00	5.36E-01	2.40E-01	
-4.55E 02	4.46E 03	4.45E 03									
-9.10E 02	8.92E 03	8.91E 03	8.91E 03								
-1.37E 03	1.34E 04										
-1.82E 03	1.78E 04										
-2.28E 03	2.23E 04										
-2.73E 03	2.68E 04	2.67E 04									
-3.19E 03	3.12E 04										
-3.64E 03	3.57E 04										
-4.10E 03	4.01E 04										
-4.55E 03	4.46E 04										
0.0	0.0	7.00E 03	1.40E 04	2.10E 04	2.80E 04	3.50E 04	4.20E 04	4.90E 04	5.60E 04	6.30E 04	7.00E 04

WAVE LENGTH

DEPTH	U	VELOCITY											
5.00E-01	2.34E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.50E-01	2.34E-02	2.22E-02	1.89E-02	1.37E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	2.34E-02	2.22E-02	1.89E-02	1.37E-02	7.22E-03	7.42E-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-2.50E-01	2.34E-02	2.22E-02	1.89E-02	1.37E-02	7.22E-03	7.42E-08	-7.22E-03	0.0	0.0	0.0	0.0	0.0	0.0
-5.00E-01	2.34E-02	2.22E-02	1.89E-02	1.37E-02	7.22E-03	7.42E-08	-7.22E-03	-1.37E-02	-1.89E-02	-2.22E-02	-2.34E-02		
-4.55E 02	2.33E-02	2.21E-02	1.88E-02	1.37E-02	7.19E-03	7.39E-08	-7.19E-03	-1.37E-02	-1.88E-02	-2.21E-02	-2.33E-02		
-9.10E 02	2.32E-02	2.21E-02	1.88E-02	1.36E-02	7.17E-03	7.36E-08	-7.17E-03	-1.36E-02	-1.88E-02	-2.21E-02	-2.32E-02		
-1.37E 03	2.31E-02	2.20E-02	1.87E-02	1.36E-02	7.14E-03	7.34E-08	-7.14E-03	-1.36E-02	-1.87E-02	-2.20E-02	-2.31E-02		
-1.82E 03	2.31E-02	2.19E-02	1.87E-02	1.36E-02	7.13E-03	7.32E-08	-7.13E-03	-1.36E-02	-1.87E-02	-2.19E-02	-2.31E-02		
-2.28E 03	2.30E-02	2.19E-02	1.86E-02	1.35E-02	7.11E-03	7.30E-08	-7.11E-03	-1.35E-02	-1.86E-02	-2.19E-02	-2.30E-02		
-2.73E 03	2.30E-02	2.18E-02	1.86E-02	1.35E-02	7.10E-03	7.29E-08	-7.10E-03	-1.35E-02	-1.86E-02	-2.18E-02	-2.30E-02		
-3.19E 03	2.29E-02	2.18E-02	1.86E-02	1.35E-02	7.09E-03	7.28E-08	-7.09E-03	-1.35E-02	-1.86E-02	-2.18E-02	-2.29E-02		
-3.64E 03	2.29E-02	2.18E-02	1.85E-02	1.35E-02	7.08E-03	7.27E-08	-7.08E-03	-1.35E-02	-1.85E-02	-2.18E-02	-2.29E-02		
-4.10E 03	2.29E-02	2.18E-02	1.85E-02	1.35E-02	7.07E-03	7.27E-08	-7.07E-03	-1.35E-02	-1.85E-02	-2.18E-02	-2.29E-02		
-4.55E 03	2.29E-02	2.18E-02	1.85E-02	1.35E-02	7.07E-03	7.27E-08	-7.07E-03	-1.35E-02	-1.85E-02	-2.18E-02	-2.29E-02		
0.0	0.0	7.00E 03	1.40E 04	2.10E 04	2.80E 04	3.50E 04	4.20E 04	4.90E 04	5.60E 04	6.30E 04	7.00E 04		

WAVE LENGTH

Table 4

Table 5

AIRY WAVE CALCULATION FOR AIRY TSUNAMI				WAVE LENGTH	HEIGHT
AMPLITUDE	1.0000E 00	DEPTH	4.5500E 03	WAVE LENGTH	1.4000E 05
WAVE SPEED	2.0571E 02	PERIOD	6.6757E 02	GRAVITY	9.8000E 00
GROUP VELOCITY	2.0686E 02	ENERGY PER SURFACE AREA	4.9000E 00		
				9.0	4.5510C00000F 03
				6.9999609375E 03	4.55094921875E 03
				1.3999921875E 04	4.5508C859375E 03
				2.099982813E 04	4.55058593750E 03
				2.7999843750E 04	4.5503C8593750E 03
				3.499980468E 04	4.5500C000000E 03
				4.199976525E 04	4.5496875000E 03
				4.8999726563E 04	4.54941015625E 03
				5.5999687500E 04	4.5491875000E 03
				6.2999648439E 04	4.54904687500E 03
				6.9999375000E 04	4.5490C000000E 03

Table 6

Table 7

AIRY WAVE CALCULATION FOR 660 SEC PERIOD TSUNAMI SHOALING TO 100 METERS												WAVE LENGTH	HEIGHT
AMPLITUDE 1.800E 00 DEPTH 1.000E 02 WAVE LENGTH 2.100E 04												0.0	1.01799987793E 02
WAVE SPEED 3.1300E 01 PERIOD 6.7092E 02 GRAVITY 9.800E 00												1.0499997558E 03	1.C11898804E 02
GROUP VELOCITY 3.1291E 01 ENERGY PER SURFACE AREA 1.587E 01												2.09999951172E 03	1.C1456222534E 02
DEPTH 1.80E 00 2.59E-04 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0												3.14999926758E 03	1.01C58013916E 02
9.00E-01 8.82E 00 7.96E 00 5.45E 00 1.55E CC 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0												4.19999609375E 03	1.C0556228638E 02
0.0 1.76E 01 1.68E 01 1.43E 01 1.04E 01 5.45E 00 8.97E-05 0.0 0.0 0.0 0.0 0.0 0.0 0.0												5.2499921d750E 03	1.C00000000000E 02
-9.00E-01 2.65E 01 2.56E 01 2.31E 01 1.52E 01 1.43F 01 8.82E CC 3.37E 00 0.0 0.0 0.0 0.0 0.0 0.0												6.29998828125E 03	9.54437713623E 01
-1.80E 00 3.53E 01 3.44E 01 3.19E 01 2.80F 01 2.31E 01 1.76E 01 1.22E 01 7.27E CC 3.37E 00 8.64E-01 3.05E-04												7.34998437500E 03	9.89419860840E 01
-1.00E 01 1.16E 02 1.15E 02 1.12E 02 1.08E 02 1.03E 02 9.80E 01 9.25E 01 F.76E C1 E.37E C1 8.12E 01 8.04E 01												8.39998046875E 03	9.8543774658E 01
-2.00E 01 2.14E 02 2.13F 02 2.10E 02 2.06F 02 2.01E 02 1.96E 02 1.91E 02 1.86E 02 1.82E 02 1.79E 02 1.78E 02												8.44997656250E 03	9.82881011963E 01
-3.00E 01 3.12E 02 3.11E 02 3.08E 02 3.04E 02 2.99E 02 2.94E 02 2.89E 02 2.84E 02 2.80E 02 2.77E 02 2.76E 02												1.04999726563E 04	9.81999965482E 01
-4.00E 01 4.10E 02 4.09E 02 4.06E 02 4.02E 02 3.97E 02 3.92E 02 3.87E 02 3.82E 02 3.78E 02 3.75E 02 3.74E 02												5.00E 01	5.00E 01
-5.00E 01 5.CHE 02 5.07E 02 5.04E 02 5.00E 02 4.95E 02 4.90E 02 4.85E 02 4.80E 02 4.76E 02 4.73E 02 4.72E 02												6.00E 01	6.00E 01
-6.00E 01 6.C6E 02 6.05E 02 6.02E 02 5.98E 02 5.93E 02 5.88E 02 5.83E 02 5.78E 02 5.74E 02 5.71E 02 5.70E 02												7.00E 01	7.00E 01
-7.00E 01 7.04E 02 7.03E 02 7.00E 02 6.96E 02 6.91E 02 6.86E 02 6.81E 02 6.76E 02 6.72E 02 6.69E 02 6.68E 02												8.00E 01	8.00E 01
-8.00E 01 8.C2E 02 8.01E 02 7.98E 02 7.94E 02 7.89E 02 7.84E 02 7.79E 02 7.74E 02 7.70E 02 7.67E 02 7.66E 02												9.00E 01	9.00E 01
-9.00E 01 9.00E 02 8.99E 02 8.96E 02 8.92E 02 8.87E 02 8.82E 02 8.77E 02 8.72E 02 8.68E 02 8.65E 02 8.64E 02												1.00E 02	1.00E 02
-1.00E 02 9.98E 02 9.97E 02 9.94E 02 9.90E 02 9.85E 02 9.80F 02 9.75E 02 9.70E 02 9.66E 02 9.63E 02 9.62E 02												0.0	0.0
0.0 0.0 1.05E 03 2.10E 03 3.15E 03 4.20E 03 5.25E 03 6.30E 03 7.35E 03 8.40E 03 9.45E 03 1.05E 04												WAVE LENGTH	WAVE LENGTH
DEPTH U VELOCITY												0.0	0.0
1.80E 00 5.64E-01 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0												9.00E-01 5.64E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 0.0 0.0 0.0 0.0 0.0 0.0	
0.0 5.64E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 0.0 0.0 0.0 0.0 0.0 0.0												-9.00E-01 5.64E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 0.0 0.0 0.0 0.0 0.0 0.0	
-1.80E 00 5.64E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.64E-01												-1.00E 01 5.64E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.64E-01	
-2.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01												-3.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01	
-4.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01												-5.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01	
-6.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01												-7.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01	
-8.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01												-9.00E 01 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01	
-1.00E 02 5.63E-01 5.36E-01 4.56E-01 3.31E-01 1.74E-01 2.86E-06 -1.74E-01 -3.31E-01 -4.56E-01 -5.36E-01 -5.63E-01												0.0 0.0 1.05E 03 2.10E 03 3.15E C3 4.20E 03 5.25E 03 6.30E 03 7.35E 03 F.40F 03 9.45F 03 1.05E 04	
0.0 0.0 1.05E 03 2.10E 03 3.15E C3 4.20E 03 5.25E 03 6.30E 03 7.35E 03 F.40F 03 9.45F 03 1.05E 04 WAVE LENGTH												WAVE LENGTH	WAVE LENGTH
DEPTH V VELOCITY												0.0 0.0	0.0 0.0
1.80E 00 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0												9.00E-01 5.21E-03 1.00E-02 1.3PE-C2 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0	
0.0 0.0 5.21E-03 9.91E-03 1.36E-02 1.60E-02 1.69E-02 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0												-9.00E-01 5.16E-03 5.82E-03 1.35E-02 1.59E-02 1.67E-02 1.59E-C2 0.0 0.0 0.0 0.0 0.0 0.0 0.0	
-1.80E 00 0.0 5.12E-03 9.73E-03 1.34E-02 1.57E-02 1.66E-02 1.57E-02 1.34F-02 9.73E-03 5.12E-03 2.31E-07												-1.00E 01 4.69E-03 8.92E-03 1.23E-02 1.44E-02 1.52F-02 1.44E-02 1.23F-02 8.92E-03 4.69E-03 2.12E-07	
-2.00E 01 0.0 4.17E-03 7.93E-03 1.09E-02 1.28E-02 1.35E-02 1.28E-02 1.09E-02 7.93E-03 4.17E-03 1.89E-07												-3.00E 01 3.65E-03 6.94E-03 9.55E-03 1.12E-02 1.18E-02 1.12E-02 9.55E-03 6.94E-03 3.65E-03 1.65E-07	
-4.00E 01 0.0 3.12E-03 5.94E-03 8.18E-03 9.62E-03 1.01E-02 9.62E-03 8.18E-03 5.94E-03 3.12E-03 1.41E-07												-5.00E 01 2.60E-03 4.95E-03 6.82E-03 8.02E-03 8.43F-03 8.02E-03 6.82E-03 4.95E-03 2.60E-03 1.18E-07	
-6.00E 01 0.0 2.08E-03 3.96E-03 5.45E-03 6.41E-03 6.74E-03 6.41E-03 5.45E-03 3.96E-03 2.08E-03 9.42E-08												-7.00E 01 1.56E-03 2.97E-03 4.09E-03 4.81E-03 5.06E-03 4.81E-03 4.09E-03 2.97E-03 1.56E-03 7.07E-08	
-8.00E 01 0.0 1.04E-03 1.98E-03 2.73E-C3 3.21F-03 3.37E-03 3.21F-03 2.73E-03 1.98E-03 1.04E-03 4.71E-08												-9.00E 01 5.21E-04 9.91E-04 1.36E-03 1.60E-03 1.69E-03 1.60E-03 1.36E-03 9.91E-04 5.21E-04 2.36E-08	
-1.00E 02 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0												0.0 0.0 1.05E 03 2.10E 03 3.15E 03 4.20F 03 5.25F 03 6.30F 03 7.35F 03 F.4CE 03 9.45F 03 1.05E 04	
0.0 0.0 1.05E 03 2.10E 03 3.15E 03 4.20F 03 5.25F 03 6.30F 03 7.35F 03 F.4CE 03 9.45F 03 1.05E 04 WAVE LENGTH												WAVE LENGTH	WAVE LENGTH

Table 8

Table 9

AIRY WAVE CALCULATION FCR 660 SEC PERIOD TSUNAMI SHOALING TO 500 METERS					WAVE LENGTH	HEIGHT	
AMPLITUDE	1.6000E 00	DEPTH	5.0000E 02	WAVE LENGTH	4.6500E 04	0.0	5.01599853516E 02
WAVE SPEED	6.9947E 01	PERIOD	6.6479E 02	GRAVITY	9.8000F 00	2.32499975586E 03	5.01521484375E 02
GROUP VELOCITY	6.9941E 01	ENERGY PER SURFACE AREA	1.2544E 01			4.64999609375E 03	5.01294189453E 02
						6.97499218750E 03	5.00940426988E 02
						9.2999882L25E 03	5.0.C0940426988E 02
						1.16249843750E 04	5.0.C00000000000E 02
						1.39499804688E 04	5.0.S00000000000E 02
						1.62749765625E 04	4.99503532172E C2
						1.85999726563E 04	4.98705566406E 02
						2.09249687500E 04	4.98478271484E 02
						2.32499648438E 04	4.98399902344E 02

DEPTH	U	VELOCITY										
1.60E 00	2.24E-01	0.0	0.0	C.C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.00E-01	2.24E-01	2.13E-01	1.81E-01	1.32E-01	0.0	0.0	0.0	0.0	C.C	C.C	0.0	0.0
0.0	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.93E-02	9.26E-07	0.0	0.0	C.C	C.C	0.0	0.0
-8.00E-01	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.93E-02	9.26E-07	-6.93E-02	0.0	C.C	C.C	0.0	0.0
-1.60E 00	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.93E-02	9.26E-07	-6.93E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-5.00E 01	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.92E-02	9.25E-07	-6.92E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-1.00E 02	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.92E-02	9.25E-07	-6.92E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-1.50E 02	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.92E-02	9.24E-07	-6.92E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-2.00E 02	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.92E-02	9.24E-07	-6.92E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-2.50E 02	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.92E-02	9.24E-07	-6.92E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-3.00E 02	2.24E-01	2.13E-01	1.81E-01	1.32E-01	6.91E-02	9.24E-07	-6.91E-02	-1.32E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-3.50E 02	2.24E-01	2.13E-01	1.81E-01	1.31E-01	6.91E-02	9.24E-07	-6.91E-02	-1.31E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-4.00E 02	2.24E-01	2.13E-01	1.81E-01	1.31E-01	6.91E-02	9.24E-07	-6.91E-02	-1.31E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-4.50E 02	2.24E-01	2.13E-01	1.81E-01	1.31E-01	6.91E-02	9.23E-07	-6.91E-02	-1.31E-01	-1.81E-01	-2.13E-01	-2.24E-01	
-5.00E 02	2.24E-01	2.13E-01	1.81E-01	1.31E-01	6.91E-02	9.23E-07	-6.91E-02	-1.31E-01	-1.81E-01	-2.13E-01	-2.24E-01	
0.0												
	WAVE LENGTH											
		2.32E 03	4.65E 03	6.67E 03	9.30E 03	1.16E 04	1.19E 04	1.63E 04	1.86E 04	2.09E 04	2.32E 04	

Table 10